

The ISS Increments 3 & 4 Test Report

For the **Active Rack Isolation System**

ISS Characterization Experiment

ARIS-ICE

http://iss-www.jsc.nasa.gov/ss/issapt/aris_ice/

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ARIS-ICE Increments 3 & 4 On Orbit Operational Accomplishments & Results

Abstract

The purpose of ARIS-ICE is to improve, optimize then operationally test and document the performance of the ARIS system on the International Space Station. The ICE program required testing across a full 3 increments (2 through 4). This paper represents the operational report summarizing our accomplishments through the third and fourth increment of testing. The main objectives and results of the increment two testing are discussed in **The Increment two Operational Report**. This report can be obtained from the ISS Payloads Office or from (<http://iss-www.jsc.nasa.gov/ss/issapt/payofc/OZ3/ARIS.html>). In summary these were to ensure the smooth and successful activation of the system and correct operational issues related to long term testing. Then the follow on increment 3 & 4 testing encompassed the majority of the on orbit performance assessments and improvements made to the ARIS system. The intent here is to report these preliminary results of the increment 3 & 4 ARIS-ICE testing as well as the ARIS system improvements made for our users and customers.

The ISS **Increment 3 & 4 Test Report** For the **Active Rack Isolation System** **ISS Characterization Experiment** **ARIS-ICE**

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ARIS-ICE Increments 3 & 4 On Orbit **Operational Accomplishments & Results**

I. INTRODUCTION

A. Hypothesis

The purpose of ARIS-ICE was to improve, optimize then operationally test and document the performance of the ARIS system on the International Space Station. The ICE program required testing across a full 3 increments (2 through 4). This paper represents the operational report summarizing our accomplishments through the third and fourth increment of testing.

B. Objectives of Investigation

The main objectives and results of the increment two testing are discussed in **the increment two operational report**. This report can be obtained from the ISS Payloads Office or from the web at <http://iss-www.jsc.nasa.gov/ss/issapt/payofc/OZ3/ARIS.html>. In summary these were to ensure the smooth and successful activation of the system and correct operational issues related to long term testing. Then the follow on increment 3 & 4 testing encompassed the majority of the on orbit performance assessments and improvements made to the ARIS system. The intent here is to report these preliminary results of the increment 3 & 4 ARIS-ICE testing as well as the ARIS system improvements made for our users and customers.

C. Previous Mission Experience

During the previous STS79 flight of ARIS a series of operational anomalies occurred during the turn on and operational testing process. As a result ARIS underwent a series of modifications and the need for a more carefully monitored initial turn on process was identified. ICE provided this and was able to successfully implement the lessons learned from the last flight. Additionally the modifications made to the system as a result of the last flight were proven to have also successfully functioned as designed/required.

D. Background/History

ARIS is the primary vibration isolation system for the ISS microgravity (μG) research effort.

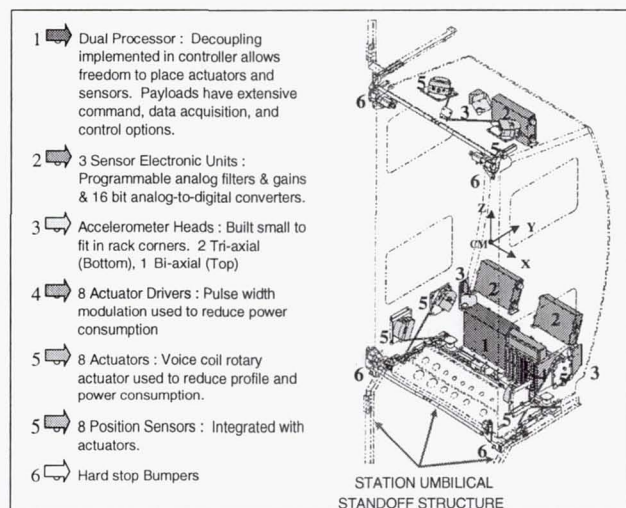


FIGURE 1: THE ARIS CONFIGURATION

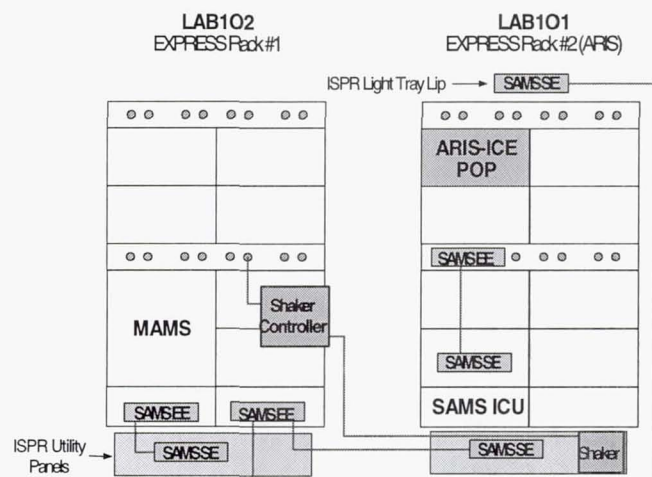


FIGURE 2: THE ARIS-ICE TEST CONFIG.

The basic ARIS & ARIS-ICE configurations are shown in Figs 1&2. ARIS was/is intended as an integrated piece of the ISS strategy to provide the program with the μG requirement for on orbit testing as documented in the ISS Vehicle Office System Specification (straight line plot in Fig 3).

E. The Payload Office's Role

NASA's Payloads Office took over management of the ARIS system for the ISS Vehicle as a result of the lessons learned from the last flight. The Payloads Office initiated a systems level approach to providing the required μG environment that

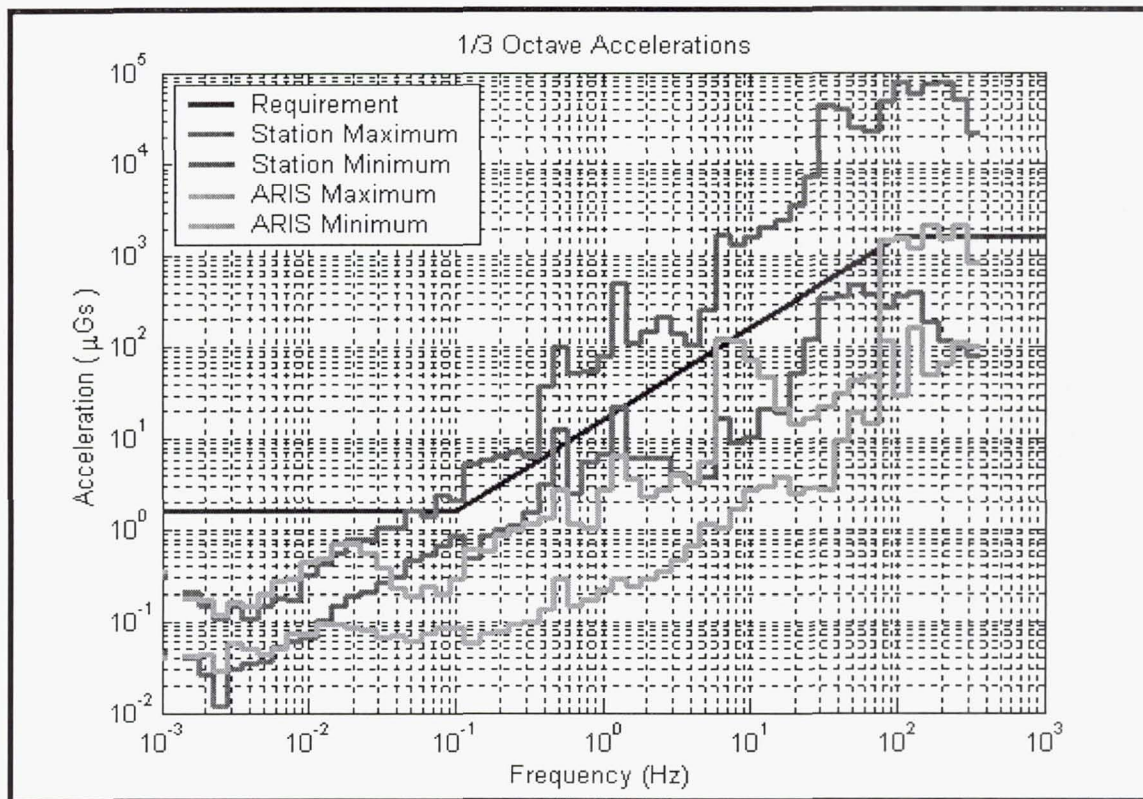


Figure 3 : Science Requirement and Measured Acceleration Levels
Station Vibration Above 5 Hz Excited With Hammer

involved identifying and optimizing ARIS' isolation capabilities first. Then working with the program to ensure that the Vehicle office implements a comprehensive strategy to produce the system spec requirement, with ARIS as the centerpiece of that strategy. The role of ICE in the big picture is to try and improve ARIS' performance as much as possible during operations and to document that performance on orbit.

F. The role of ARIS

One of the primary objectives of the International Space Station (ISS) is to provide an acceleration environment suitable for microgravity class science experiments. Microgravity experiments include many crystal growth and fluid experiments that are very sensitive to very low quasi-steady frequency acceleration. The maximum acceleration level considered acceptable for most microgravity experiments is specified in the International Space Station system spec. and is shown in Figure 3. This requirement constrains the root-mean-square (rms) acceleration level for one-third octave bandwidths. As can be seen in the figures, the rms

acceleration magnitudes below 0.1 Hz must be less than 1.6 micro-G, and above 100 Hz less than 1.6 milli-G. Early predictions indicated that the station acceleration environment could be as much as 10 times higher than the requirement.

To insure that the requirement was met at certain payload rack locations in the Space Station, an Active Rack Isolation System (ARIS) was built and tested on-orbit. The first prototype flew on a shuttle mission to the Russian MIR Space Station (STS-79) in September of 1996, and the first flight unit recently flew in April 2001 and was installed on the International Space Station in the U.S. Lab (STS-100). There are currently three types of microgravity science racks that plan to use ARIS to isolate their payloads. They are the EXpedite the PROcessing of Experiments to the Space Station (EXPRESS) rack, the Fluid Combustion Facility (FCF) rack, and the Materials Science Research Facility (MSRF) racks. All of these racks use the International Standard Payload Rack shell, mounting posts, and utility interface panel. Unique payload hardware is added to build each facility. An EXPRESS rack is shown in Figure 4, and is the

first ARIS rack that was tested on the Space Station. The rack is outfitted with power, communications, and cooling systems to support microgravity payloads. Payloads can be mounted at any of eight standard Shuttle mid-deck lockers or in two Standard Interface Rack (SIR) drawers at the bottom of the rack.

G. Details of the ARIS Concept

The ARIS concept is to isolate the entire rack. The rack is isolated by detaching it from the station structure (so that it is free to move) and then holding it motionless via an active control system. The active control system consists of inertial accelerometers mounted in the rack and voice coil type actuators placed between the rack and the station. Umbilicals remain connected to the rack to support power, fluid cooling, and data communication as required by the science payload. Undesirable forces transmitted from the station to the rack by the umbilicals are canceled by the active control system.

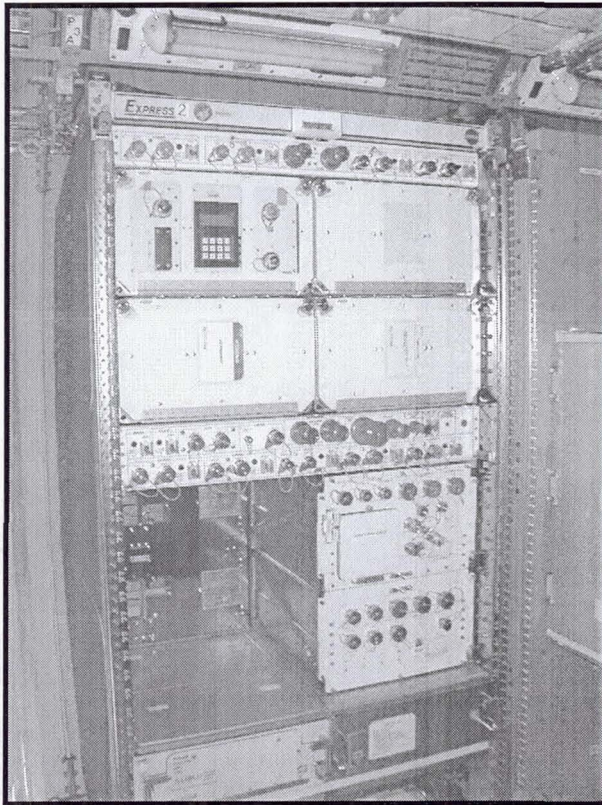


Figure 4 : Space Station EXPRESS Rack

The ARIS hardware configuration is shown in Figs 1,2&4. Acceleration is sensed at accelerometer heads located in corners of the rack. Each head contains an orthogonal set of single axis proof-mass accelerometers. Hard stop bumpers located on the front and bottom of the rack prevent the rack from impacting non-ARIS structure. The bumpers constrain the rack so that it can not move more than 0.5 inches in any direction from its center position. Low authority position feedback is blended with acceleration feedback to keep the rack away from the bumpers so that Station structural vibrations may be isolated without impact interruptions.

H. Details of the ARIS-ICE Test Set-up

Full ARIS characterization testing required the development of additional hardware. This required ICE hardware included a shaker system to excite station vibration, a space station acceleration measurement systems to measure the vibration, and a computer to support command and data handling. The ICE test configuration is illustrated in Figure

2. Space station accelerations were measured using the Space Acceleration Measurement System (SAMS) and the Microgravity Acceleration Measurement System (MAMS). The SAMS Sensor Enclosures (SEs), or sensor heads, each contained an orthogonal set of single axis accelerometers and were used to measure Station acceleration above 0.01 Hz. Three heads were mounted around the rack, one at the top actuator interface, one at the bottom umbilical interface, and one on the adjacent rack umbilical interface panel. The MAMS unit was used to measure very low frequency accelerations below 0.01 Hz. The rack accelerations were measured using the ARIS acceleration measurement system and one SAMS head located on the Physics of Colloids in Space (EXPPCS) experiment locker. To help resolve isolation above 1 Hz, a shaker was mounted on station structure beneath the rack and used to excite station vibration. The crew also used a small hammer to excite the structure by tapping at specified locations around the rack. Ground command, data handling, and data storage capability was provided by the ARIS-ICE Payload On-orbit Processor (POP). Flight data was collected by the POP for one full year beginning in June of 2001 and over 1700 test runs were completed.

The rack was launched with the POP in the upper left locker and with EXPPCS using all 4

lower middeck lockers. The SAMS Interim Control Unit (ICU) was located in the bottom

Function	PROTO	EXPRESS	FCF	MSRF
Ground	X	X	X	X
Main	X	X	X	X
Safing	X	X	X	X
1553 A		X	X	X
1553 B	X	X	X	X
Video		X	X	X
High Rate Data	X	X	X	X
FDS		X	X	X
Ethernet	X	X	X	X
Ethernet Data	X	X	X	X
Cooling	X	X	X	X
Cooling	X	X	X	X
Waste		X	X	X
Vacuum Resource			X	X
GN2	X	X	X	X
Laptop	X ¹	X	X	X
Pump	X ²			
Fiber			X ³	
1. Used Video Interface 2. Used FDS Interface 3. Data cable run between two adjacent FCF FCF – Fluid Combustion Facility MSRF – Material Science Research Facility				

Table 1 : Umbilical Configurations

left SIR drawer, and spare ARIS-ICE umbilicals were located in the right SIR drawer. The locker below the POP was used for stowage of other ARIS-ICE hardware, such as the shaker, when not in use. The remaining top 2 middeck locker locations remained empty until the Zeolite Crystal Growth (ZCG) payload was added in December of 2001.

I. Umbilical Alternatives

Power, thermal cooling, vacuum, and data lines are provided to all station racks at interfaces below the rack. A list of the umbilicals provided is listed in Table 1 for the station ARIS racks, and for the prototype rack.

The prototype set of umbilicals had been designed to have low stiffness to improve isolation performance, but the performance benefits were not fully realized due to hysteresis. Post prototype mission ground data showed that the stiffness increases as the amplitude of motion decreases. The amplitudes of motion are small at higher frequencies, resulting in higher stiffness and lost performance. The stiffness also varies as the rack moves away from its center position. Prior to the mission, the stiffness was only measured over one large amplitude of motion. The lower large motion stiffness values, not the small motion higher stiffness values, were used in the controller to cancel stiffness.

The ARIS controller was designed to allow for measurement of the linear stiffness forces and cancel them, but has no provisions for canceling the hysteretic and flexible dynamic forces. The dynamic forces had never been measured prior to the prototype experiment. Following the experiment, an inexpensive ground test bed was made utilizing experiment hardware to measure the stiffness of each individual umbilical and its dynamic response in two directions. NASTRAN models were also built and correlated to the test data. From this it was found that the large twisted copper power umbilicals accounted for 50 percent of the stiffness and had a significant mode at 10 Hz. It was also obvious that the stranded wire had significant hysteresis. Several design options were tested and alternative sets built and flown as part of the ARIS-ICE mission. These options are listed in Table 2.

The prototype design used a heavier gauge wire to allow for 6 kW power. It had standard pressure extruded insulation, and like most of the

umbilicals, was looped to reduce its stiffness. The lighter gauge wire (3 kW) was built with loose sleeve insulation to reduced stiffness, and the loop was removed to eliminate the 10 Hz mode. The cooling water and gas hoses were also improved by using a softer type of material.

J. ARIS-ICE Controller Design

A new controller was designed to improve performance based upon the experience gained from the prototype experiment. The significant changes are listed below.

1. Filters were added to gain-stabilize the EXPRESS structural modes, and the bandwidth of the controller was increased as much as possible. A test correlated NASTRAN model of the EXPRESS rack was developed and was added to the Matlab control model.
2. The low frequency acceleration feedback gain was minimized to reduce the response to acceleration drift noise. The acceleration drift was bounded using quiescent test data collected during the prototype flight test.
3. The position authority on the rotation axes was increased to reduce rack rotations. This was done to improve the performance at locations away from the rack center of gravity. Rack rotations caused by Station translation (umbilicals torque rack) will decrease. But the rack will follow station rotation, so performance will only improve if station rotations are small.
4. The stiffness cancellation parameters were changed to use the larger small amplitude stiffness instead of the smaller large amplitude stiffness. More linear stiffness is cancelled because the small amplitude stiffness is greater than the large amplitude stiffness. This improves performance over the entire bandwidth of the controller.
5. The shape of the isolation response was changed so that ARIS isolated less around 0.01 Hz. This was done to prevent the rack from bumping into its hard stops due to low-frequency station motion. Station acceleration predictions showed that isolation around 0.01 Hz was not needed, and the total motion between the vehicle and the rack could

6. be reduced significantly by a small change to the shape of the isolation response. Performance at 0.05 Hz and above was maintained.
7. The preflight isolation performance prediction using the new updated controller is shown in Figure 5. The prediction is the worst expected performance at all payload attach locations in the rack. The model used to make the prediction was ground test correlated and included models of the rack and umbilical dynamics, uncertainty in the mass properties of the rack, and variations in the stiffness of the umbilical. Umbilical dynamics impacted performance above 7 Hz and the rack dynamics significantly impacted performance above 30 Hz. Mass and stiffness uncertainty impacted performance above 1 Hz the most. The performance prediction does include 12 db of performance improvement at 10 Hz resulting from using the 3 kW unlooped power umbilicals.

II. ICE TEST DATA & RESULTS

A. Testing Details

The alternate power umbilical designs were each installed and stiffness and isolation performance data collected. Umbilical stiffness results are presented first, followed by isolation results. The isolation performance with the umbilical set that will be installed on all future station ARIS EXPRESS racks (ARIS-ICE C) is presented. This data was taken from crew awake and station tap periods. Motion between the station and the rack during a typical isolation period is also presented. Next, data is compared with the EXPRESS AAA fan and the ARIS-ICE payload fans on and off to determine their impact on performance. The flexible response of the EXPRESS rack is shown and stability margins discussed. Finally, performance is predicted when the station structure assembly is complete and all station vibration sources operating.

B. Umbilical Stiffness Results

The measured stiffness ranges of four flight umbilical configurations are listed in Table 2. The range was determined by measuring the stiffness for small amplitude motion (0.05 inches peak to peak) and for large amplitude motion (0.5 inches peak to peak). The stiffness is higher

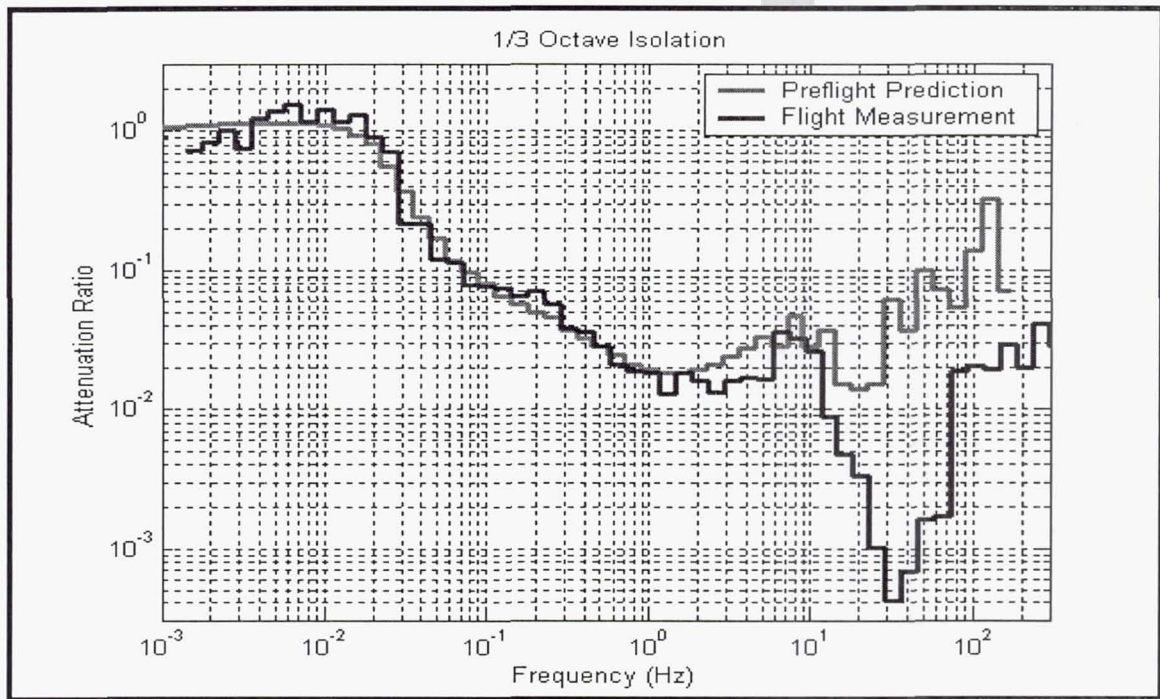


Figure 5 : Predicted and Measured Isolation Performance

Power Set	ARIS-ICE B	ARIS-ICE A	ARIS-ICE C	ARIS-ICE C
Main Power	6 kW Looped Pressure Extruded Silicon Jacket	6 kW Unlooped Loose Expanded Teflon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket
Safing Power	6 kW Looped Pressure Extruded Silicon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket
GN2 Included	No	No	No	Unlooped Teflon Bellows Braided Nomex Sleeve
X Stiffness (lb/ft)	84 – 210	47 – 73	47 – 64	65 – 125
Y Stiffness (lb/ft)	99 – 227	66 – 136	65 – 93	97 – 193
Z Stiffness (lb/ft)	109 – 386	58 – 123	58 – 85	85 – 164

Table 2 – Power Umbilical Configurations and Stiffness

Test	Number Of Windows	Window Duration (sec)	Overlap	Frequency Plotted
5 Hour	14	2097.152	50 %	0.001 – 0.1 Hz
5 Hour	121	262.144	50 %	0.1 Hz – 5 Hz
9 Minute	127	8.192	50 %	5 Hz – 300 Hz

Table 3 : Performance Data Analysis Parameters

for small amplitudes. As can be seen in table 2, the two 3 kW teflon jacketed power umbilicals (ARIS-ICE C) alone reduced the small amplitude stiffness of the entire baseline 6 kW set (ARIS-ICE B) by 2.5 to 4.5 times. The range of stiffness is also significantly reduced. Addition of the gaseous nitrogen (GN2), which is the only non-looped hose, doubled the small amplitude stiffness. It was originally designed to be looped, but the hose had to be redesigned to meet pressure requirements. The hose was changed from a soft viton material which could be preformed in a loop shape to a bellows type hose with a braided sleeve.

C. Isolation Performance

Station and rack acceleration levels during crew awake periods are shown in Figure 3. Several windows of data were used and the maximum and minimum levels are shown. The acceleration magnitudes are plotted as the root-mean-square (rms) acceleration level per one-third octave bandwidths. The Station level was resolved from the SAMS head located on the umbilical standoff structure beneath the rack. The rack level was resolved from the three ARIS heads on the rack. Each head has three linear accelerometers that are orthogonal to one another. The rms 1/3 octave band level was computed for each accelerometer, then the three levels for each head were root-sum-squared to produce a single magnitude. The rack head accelerations were compared over all windows and the maximum and minimum envelopes are plotted. The envelope of the SAMS head accelerations is also plotted.

A 5-hour test and 9-minute test were used to compute the acceleration and isolation levels shown. The data was split into windows as listed in Table 3.

Flight Engineer Carl Walz excited the Station Structure by tapping the umbilical standoff structure using the small hammer during the 9-minute test with the AAA fan turned off. Typical

Station acceleration levels flatten off above 5 Hz to levels shown at about the Station Minimum above 20 Hz. The minimum levels were obtained during windows in-between the hammer strikes. As can be seen, these levels are too low to allow accurate measurement of isolation performance. The maximum levels obtained during the hammer strikes are up to two orders of magnitude higher, thus providing a better estimate.

The corresponding isolation is plotted in Figure 5. The isolation was computed for all three ARIS heads, but only the worst of the three is shown. As can be seen in the figure, the isolation measurement follows the prediction up to 10 Hz, then becomes much better. The isolation performance was expected to be generally better than the prediction, but the prediction was made with the softer GN2 hose. Better performance was realized when the GN2 hose was removed.

D. Station Motion

Relative motion between the station and the rack is shown during a 1-hour test run in Figure 6. The amount of motion is important because the total range of relative motion is limited to 1 inch in each direction. As can be seen there is significant motion in the X direction. It was determined that the X axis motion was due to the station moving in response to crew movement down the module centerline. This was validated by station acceleration measurements and by correlated motion observed during video transmission. Conservation of momentum requires that the velocity of the center of gravity of the entire station and its enclosed contents remain constant. This means that the station will move in proportion to crew motion as follows,

$$X_{\text{Station}} = \frac{\text{Crew Mass}}{\text{Station Mass}} X_{\text{Crew}}$$

The total distance that a crew member may move down the centerline (X direction) of all the modules is listed in Table 4. The Station configuration is shown in Figure 7. The total station weight at the time of the test was 283,755 lbs. So, the station will move 0.96 inches if one crewmember weighing 175 lbs moves the length of the station. The station weight will increase at assembly complete to around 1 million lbs, so the motion will decrease accordingly. The ARIS controller uses a non-linear algorithm to generate anti-bump commands to insure that the relative range of motion is not violated. These anti-bump commands are invoked regularly due to crew motion but are limited to 15 micro-Gs or less. The measured accelerations shown in Figure 3 include the effects of the anti-bump commands, which tend to slightly increase the rack acceleration below 0.1 Hz.

Module	Length (feet)
Service	43
Zarya	41.2
Unity	18
Destiny	28
Total	130.2

E. Impacts of the AAA fan

Data was collected with the Avionics Air Assembly (AAA) and the POP Fans On and Off. Data was also collected with the POP fans On and the AAA fan Off. The AAA fan is provided by EXPRESS to cool the payloads in the rack. It draws payload exhaust heat to the rear of the rack and passes it across an air-to-water heat exchanger. It is mounted in the back of the rack behind the locker mounting panel. The POP has two standard fans in the locker to circulate air. The head acceleration levels with the fans on and off are shown in Figures 8 and 9.

Figure 8 data was collected for 150 seconds and subdivided into 35 windows (50% overlap) of 8.192 seconds each. The maximum levels over all windows and over all the heads are shown. The ARIS isolation system was inactive or passive during the data collection with all fans on (AAA

On), and actively isolating during the fan off tests (AAA Off and AAA & POP Off). The stiffer 6

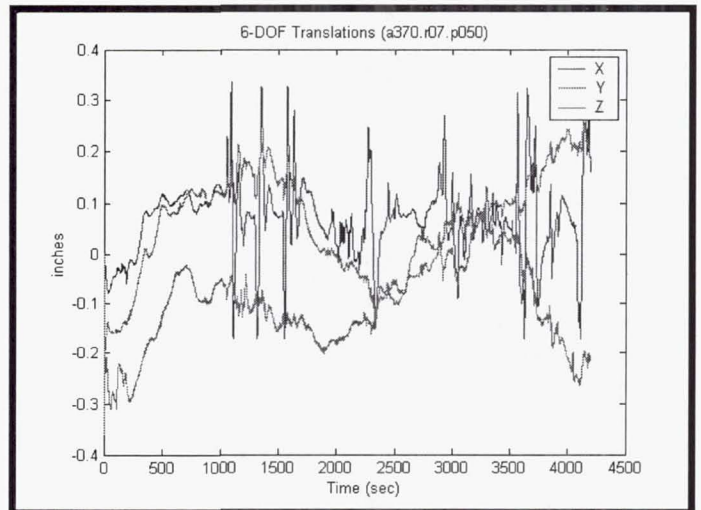


Figure 6 : Relative Motion Between Station and Rack During Active Isolation

kW power umbilicals (ARIS-ICE B) with the 10 Hz mode were installed for these tests.

The accelerations are expected to be higher below 30 Hz during the passive test because the rack is free to oscillate on the umbilicals. Above 30 Hz there is no difference between the passive and active isolation state. This is because the controller feedback rolls off at 30 Hz, so the rack behaves passively above 30 Hz even when in an active isolation state. As can be seen the POP fans have very little effect, but the AAA drives significant vibration in the 80 to 200 Hz region resulting in levels higher than the requirement at 180 Hz. The PSD's of the acceleration show many modes between 80 and 200 Hz, with the highest energy at 90 and 184 Hz.

Figure 9 data was collected with the AAA and POP fans on. The test duration was 524 seconds and again subdivided into 8.192-second windows. The levels at the three ARIS heads and the SAMS head mounted on EXPPCS are shown. The levels are the maximum over all windows. As can be seen, the levels vary at higher frequencies. One ARIS head meets the science requirement over all octave bands.

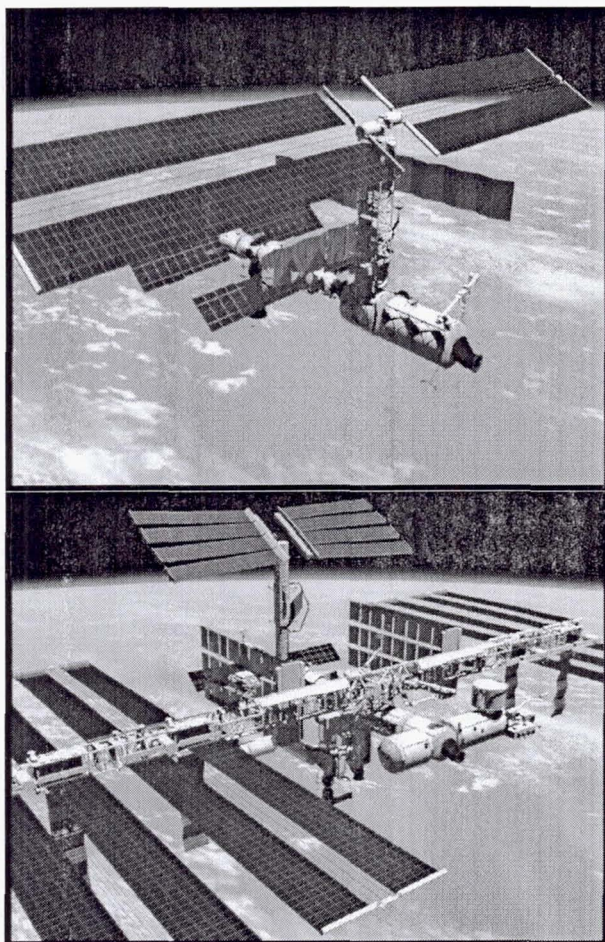


Figure 7 : Station Configurations

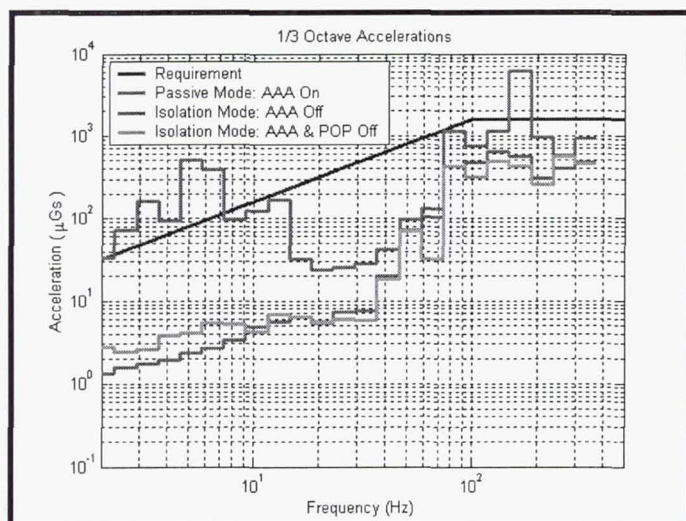


Figure 8 : Maximum Head Accelerations
With Fans On and Off

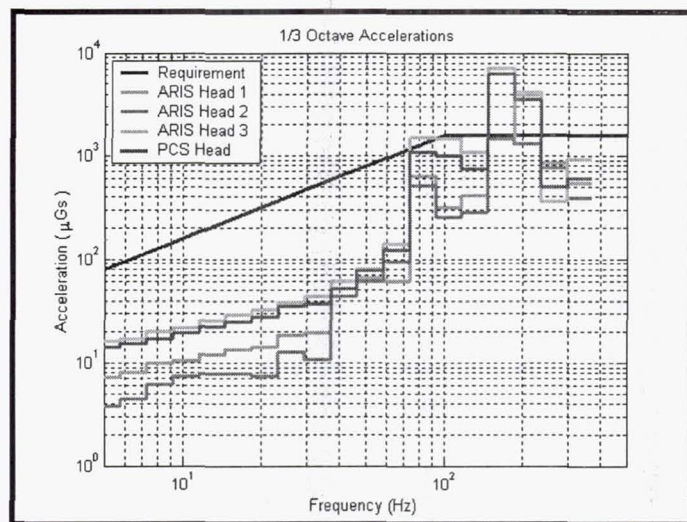


Figure 9 : Head Accelerations
With Fans On and ZCG Installed

F. Flexible Response Of The Rack

The flexible response of the rack was measured by commanding the ARIS actuators to drive the rack in a single control direction. The commanded force was a combination of superimposed sinusoids spaced every 1/30 of an octave in frequency between 30 and 300 Hz. The response in each control direction is shown in Figure 10. The first fundamental mode was measured to be 47 Hz. Strong modes also appear at 112, 146 thru 184, and 285 Hz. The objective of this test was to determine what the control stability margins were. The controller filtering characteristics had been designed prior to flight based on a ground test correlated NASTRAN model.

The preflight open loop acceleration response prediction of the controller and flexible rack is shown in Figure 11. The flexible rack model did not include modes past 150 Hz. A 30 Hz 2nd Order Filter, a 30 Hz 40 db stop band elliptical filter, and a 119 Hz notch filter were required to stabilize the modes above 35 Hz. The first fundamental mode was predicted to be 42 Hz. Preflight ground test data showed that the first mode had around 2 percent damping. The high damping was attributed to the fact that the mode shape required the entire rack to deflect and

twist. For the most part, other higher modes were merely local interactions between concentrated masses and panels with damping between 0.5 and 1 percent. This is consistent with the flight data which shows that 30 db attenuation is required at 47 Hz, and at least 50 db is required above 100 Hz. So, heavy filtering was still required.

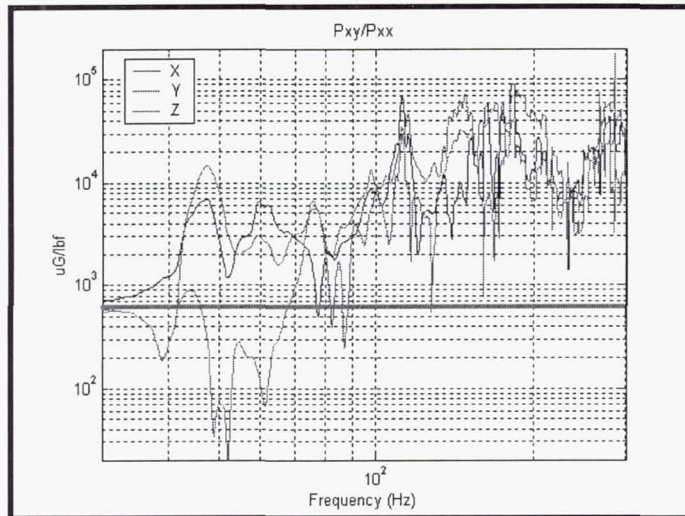


Figure 10 : Measured Forced Response Of The Rack

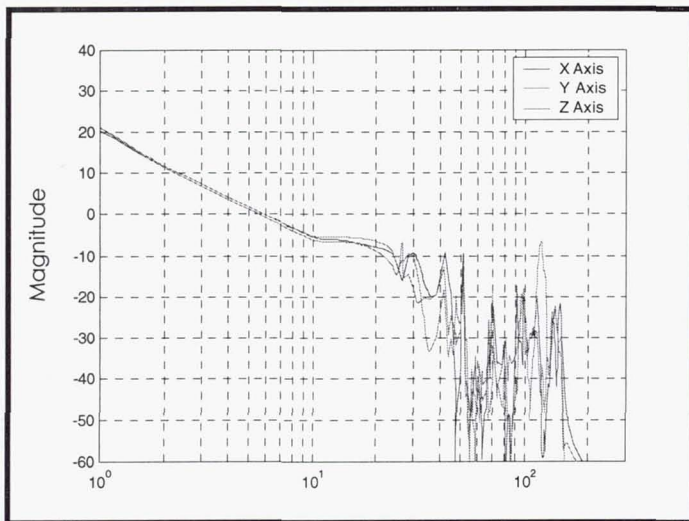


Figure 11 : Preflight Predicted Open Loop Response Stability Margins (Magnitude vs Frequency)

G. ASSEMBLY COMPLETE PREDICTION

The station structure at assembly complete will be larger (see Figure 7) and have more vibration sources as payloads are added. The Station

acceleration prediction at assembly complete is shown in Figure 12 (next page). The isolation performance shown in Figure 5 was used to predict the EXPRESS rack acceleration levels shown in Figure 11 at assembly complete. The prediction meets the science requirement. Work is currently being conducted to predict the performance for the Fluids Combustion Facility and the Microgravity Science Research Facility. Two major differences are that these facilities use a large Vacuum Resource umbilical and that the payload structure is significantly different.

III. CONCLUDING REMARKS

A. Summary

Valuable data has been collected during the ARIS International Space Station Characterization Experiment. ARIS has consistently performed extremely well over the past year such that station vibrations were isolated to levels well below the science requirement. This success was a result of lessons learned from the prototype experiment and design changes made to the umbilicals and control parameters. The unlooped GN2 hose increased the overall umbilical set stiffness, but performance was maintained mainly due to the significant decrease in overall stiffness provided by improved power umbilicals developed and tested as part of ARIS-ICE. The expected acceleration levels on an ARIS isolated EXPRESS rack after station assembly is complete is expected to meet the microgravity science requirement at frequencies below 100 Hz. Science payloads need to be designed so that vibration is not transmitted to their own science location by their own vibration sources if the science requirement is to be met at all frequencies. Performance for other ARIS isolated facilities will be dependent on the facility rack structure and on the stiffness and dynamics of the Vacuum Resource umbilical. Work on characterizing the Vacuum Resource umbilical is currently in progress. A more detailed, final report of the ARIS-ICE mission and test results will be provided to address the volumes of data collected. *This Final Report is currently scheduled to be released around the end of July 2003.*

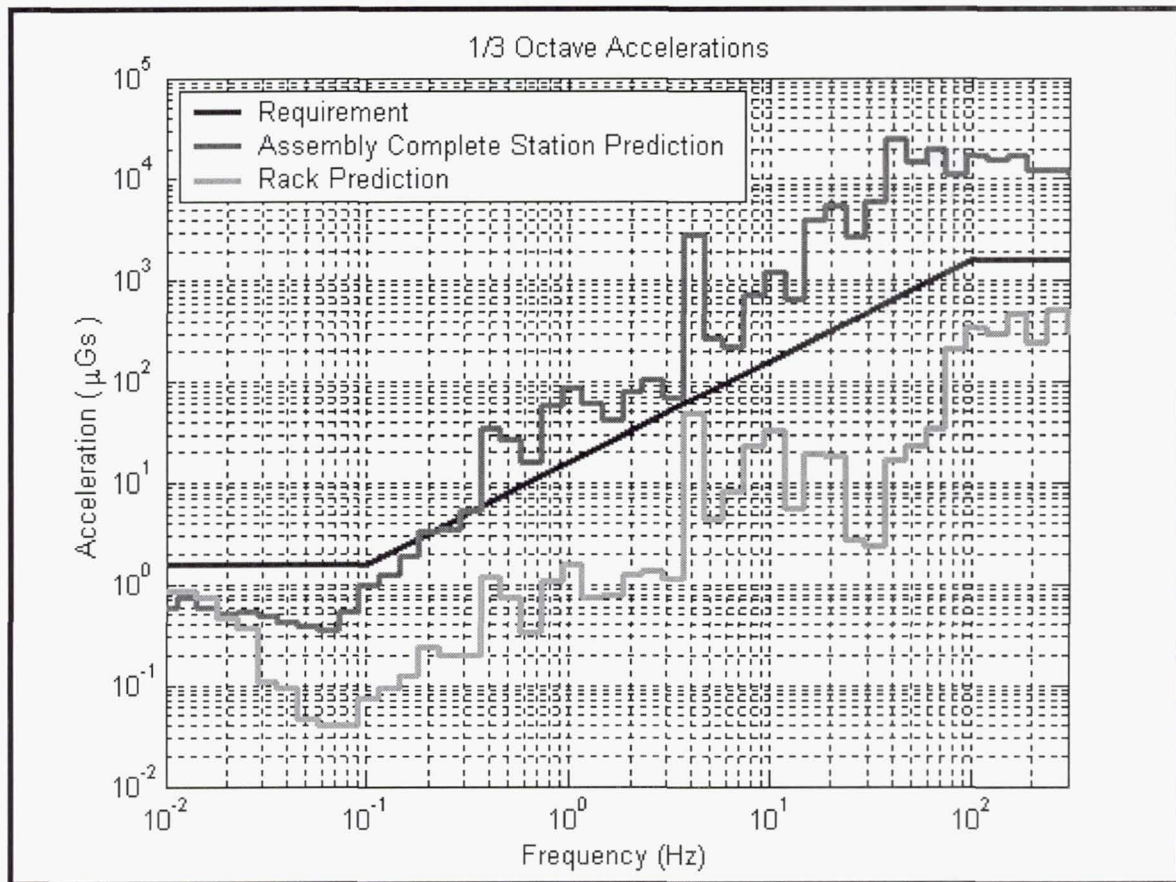


Figure 12 : Predicted Station and EXPRESS Acceleration Levels at Assembly Complete

PRELIMINARY ESTIMATES PENDING FINAL REPORT

B. CONCLUSION

The positive results reported are based on the preliminary analysis and the improvements made to the ARIS system as part of the ICE. It does appear that within the context described the desired microgravity isolation levels required for ISS uG testing are achievable within the International Space Station. This however requires constant vigilance and a proactive team staying abreast of the highlighted issues, latest data and changes to the systems. At our request (a Systems Integrator and team) this team was

created to perform this end to end function after the ARIS-ICE team is finished and disassembled as is the case now. This Systems Integration team will have to coordinate and stay abreast of all ISS microgravity issues. In this manner we will know if the assumption under which we were able to provide a desired uG (the required vibration free) environment are still in place. This is particularly critical at the later stages of the ISS assembly and in the post assembly stages. Given this proactive effort indications are that the environment required for ISS uG Science is achievable.

Executive Summary

This paper is being written to satisfy a program requirement to have increment reports for each experiment. These are to be submitted for each increment on the ISS.

The increment 2 Report has already been submitted and has been distributed for over a year. This represents the similar report for increments 3 & 4 for the ARIS-ICE Program.

In order to expedite the review we have used already existing documentation (that has already been released to the public) in putting this report out. In accordance with that the report takes the already released increment 2 report and accomplishments paper on ARIS-ICE already presented at the World Space Congress (Houston 2002) and blends them into this report.

This is essentially an ARIS-ICE increment 3 & 4 accomplishments paper in the increment report format.

Both the Increment 2 report and the World Space Congress (Houston 2002) paper that were used to make this report from are attached below this Executive Summary.

Report on ISS Increment 2 testing for
The **Active Rack Isolation System**
ISS Characterization Experiment
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**A NASA Increment 2 Operational
Accomplishments Report**

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B. Objectives of Investigation

The main objectives of the increment 2 testing are to carefully and successfully coordinate the initial ARIS turn on procedure to avoid previous anomalies (see section C below). Ensure the smooth and successful activation of the system. To address and correct any operational issues related to long term testing. To then initiate the on orbit testing and improvement of the ARIS system. Finally, to report the preliminary results of the ICE testing to our users and customers.

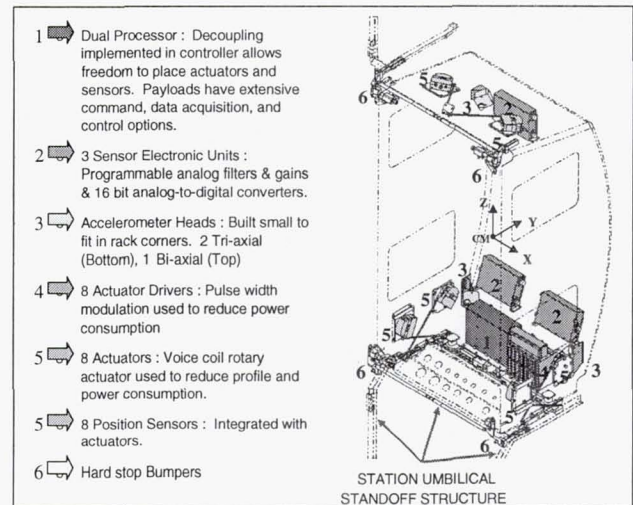
C. Previous Mission Experience

During the last flight of ARIS a series of operational anomalies occurred during the turn on and operational testing process. As a result ARIS underwent a series of modifications and the need for a more carefully monitored initial turn on process was identified. ICE provided this and was able to successfully implement the lessons learned from the last flight. Additionally the modifications made to the system as a result of the last flight were proven to have also successfully functioned as designed/required.

D. Background/History

ARIS is the primary vibration isolation system for the ISS microgravity (uG) research effort. The basic ARIS configuration is shown in Fig.1. ARIS is an integrated piece of the ISS strategy to

FIGURE 1: ARIS CONFIGURATION



provide the program uG requirement for on orbit testing as documented in the ISS Vehicle Office System Specification (straight line plot below).

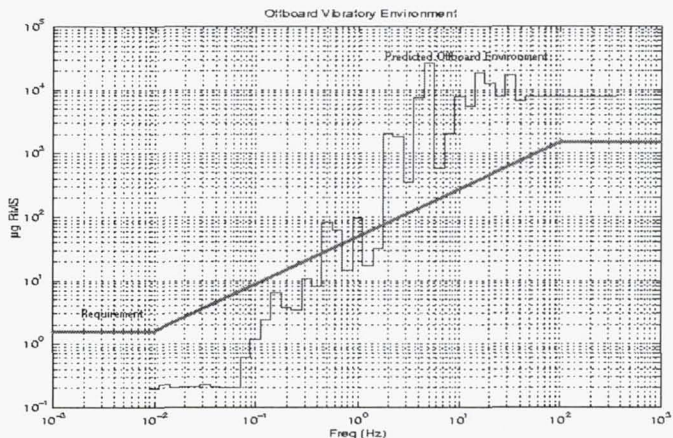


FIGURE 2: THE ISS SYSTEM SPEC

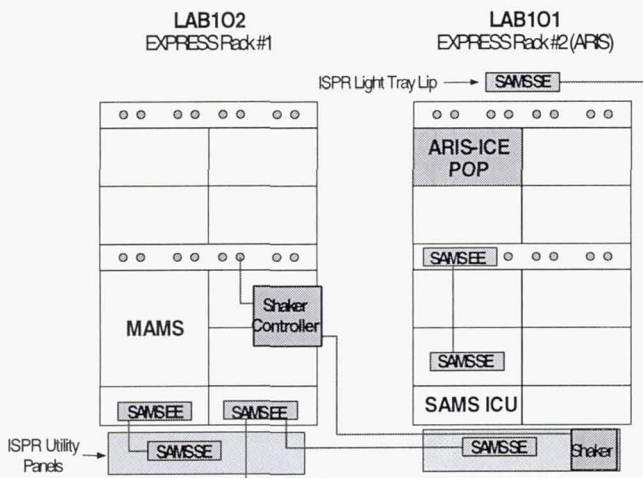
NASA's Payloads Office took over management of the ARIS system for the ISS Vehicle as a result of the lessons learned from the last flight. The payloads office has initiated a systems level approach to providing the required uG environment that involves optimizing and identifying ARIS' isolation capabilities first. Then ensuring that the Vehicle office implements a comprehensive strategy to produce the system spec requirement with ARIS as the centerpiece. The role of ICE in this strategy is to try and improve ARIS' performance as much as possible during operations and then to document what that isolation performance is on the ISS.

II. Methods/Research Operations

A. Method/Protocol

Shown below is the ARIS-ICE on orbit experimental set up which involves the use of two EXPRESS Racks in the ISS US Lab Module (Destiny). EXPRESS Rack #1 contains the Sensors (MAMS & SAMS) used to monitor the ISS environment outside the ARIS Rack (EXPRESS Rack #2). EXPRESS Rack (#2) contains the ARIS system the test computer (POP), the ARIS sensors (not shown below) and a SAMS sensor to measure the isolated environ.

FIGURE 3: ARIS ICE EXPERIMENTAL LAYOUT IN THE US DESTINY MODULE



SAMS data for ICE is recorded through the Glenn Res. Ctr. SAMS project office. The ICE team located, installed and has the capability to control the SAMS sensors.

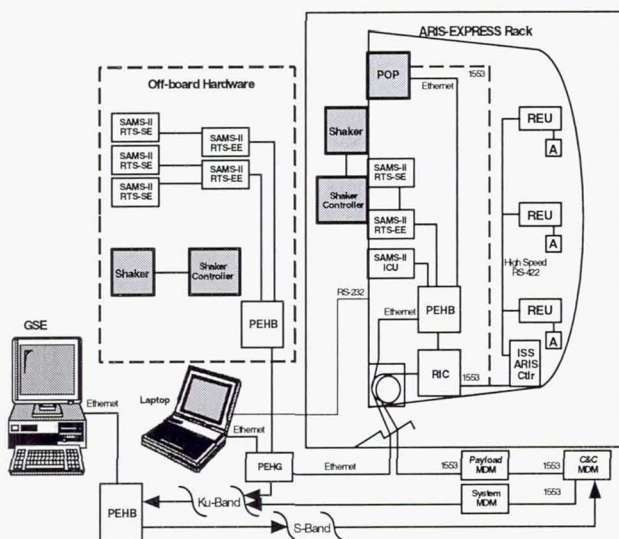


FIGURE 4: ICE COMM. AND CONTROL LINKS TO THE GROUND STATION

Using the ARIS-ICE ground stations (in Houston and in Seattle) the on orbit ARIS EXPRESS rack and the SAMS sensor the ICE experiment can be actively controlled in real time through the ISS Ku band and S band comm. links as shown.

III. Results

Through out increment 2 all the ARIS ICE testing went exceptionally well. Although operational anomalies did occur these were promptly dealt with in real time and were all able to be satisfactorily resolved. The detail of these operational anomalies are discussed below

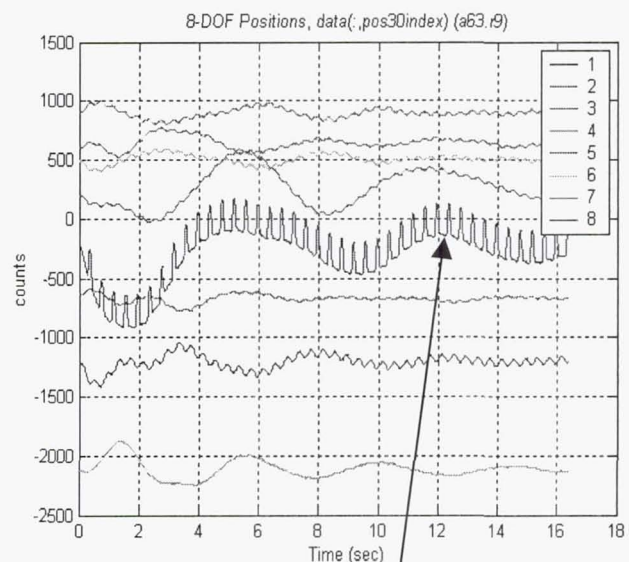
A. Preflight Anomalies

The ARIS program was unable to get an 8-gage power and a gaseous nitrogen umbilical (see figure 6C&D) delivered in time to make the 6A launch. This was a minimal impact to ICE because we were able reshuffle our testing schedule to accommodate the late umbilicals on upcoming flights.

B. On Orbit Anomalies

After initial set up and operation our real time ground data analysis (below) showed a malfunctioning actuator-pushrod system (#8). This equipment and its location are shown in figure(s) 6A&B on the next page. The plot below clearly shows the malfunctioning system data seen by the ICE ground station test team.

FIGURE 5: REAL TIME ICE TEST DATA



Mass and Inertia Test data of actuator positions while commanding actuator #8.

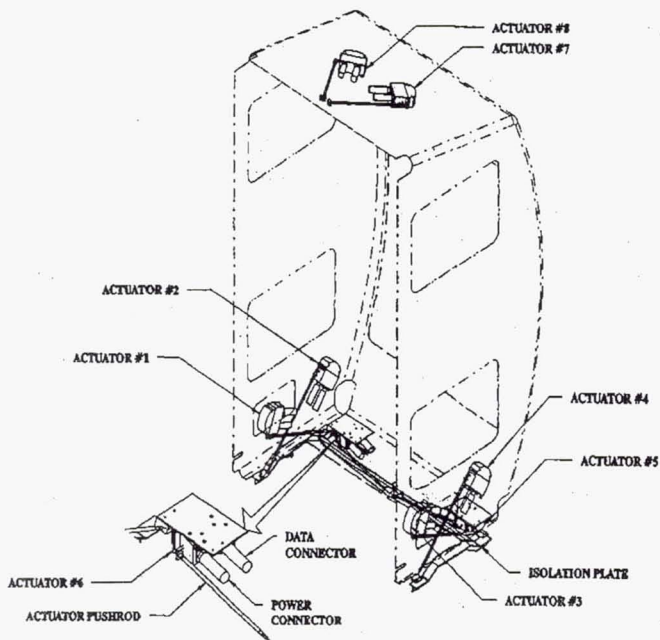


Figure 6A. Actuator #8 Location is on the top of Rack

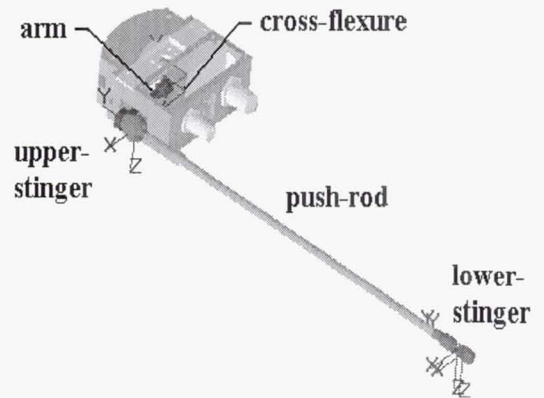


Figure 6B. The malfunctioning ARIS Actuator #8 shown with it's local Coordinate Systems

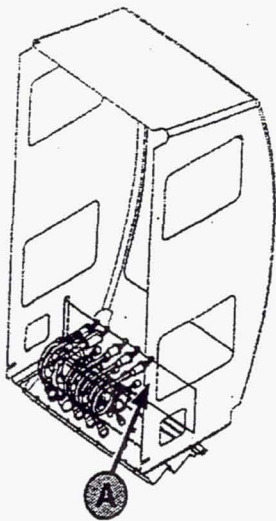


Figure 6C. Integrated Umbilical Assembly

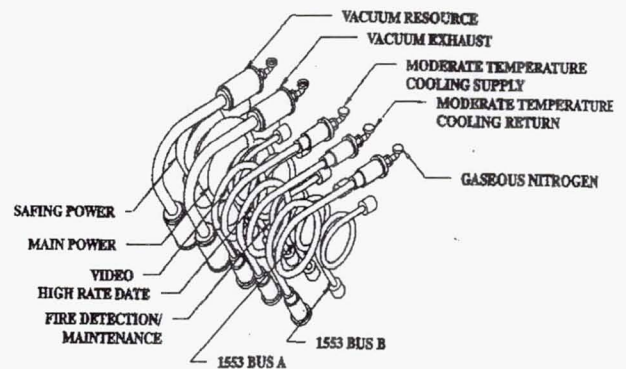
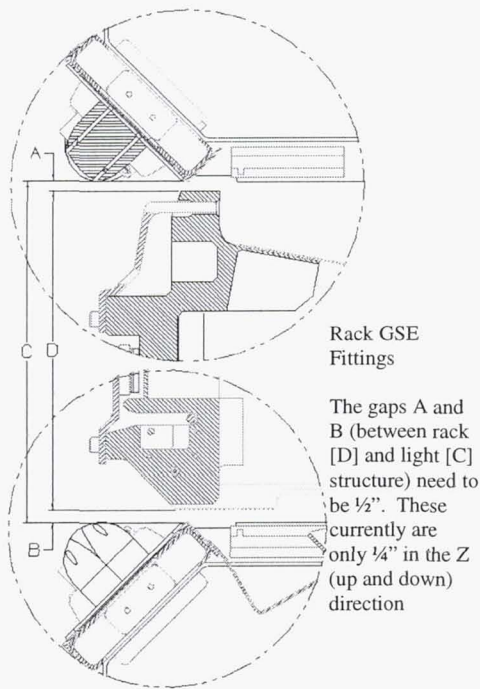


Figure 6D. Umbilical Assembly
Power and Gaseous Nitrogen hoses on ends

C. Completeness of Data

After these anomalies the ICE testing proceeded as planned and well over 500 test runs were accomplished in the increment 2 time frame. This testing served to validate the stability of the control system, confirm the success of numerous ARIS modifications made as a result of the last flight as well as provide much needed data on the ISS. Two previously unknown ISS problem areas were uncovered. The first was the structural violation of the ARIS $\frac{1}{2}$ " sway space requirement. This was due to the fact that the clearance between the end of the rack and the bottom of the ISS lighting structure was only a $\frac{1}{4}$ " (C-D below) as opposed to the required $\frac{1}{2}$ ". This was a Z-axis impact only. For the purposes of ICE testing this is something that can be dealt with but for the long term operation of the ARIS rack it is a problem that needs to be addressed.

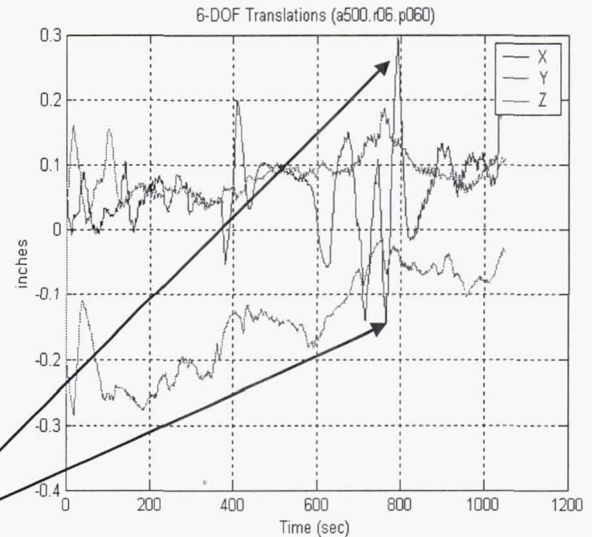
FIGURE 7: SWAY SPACE VIOLATION



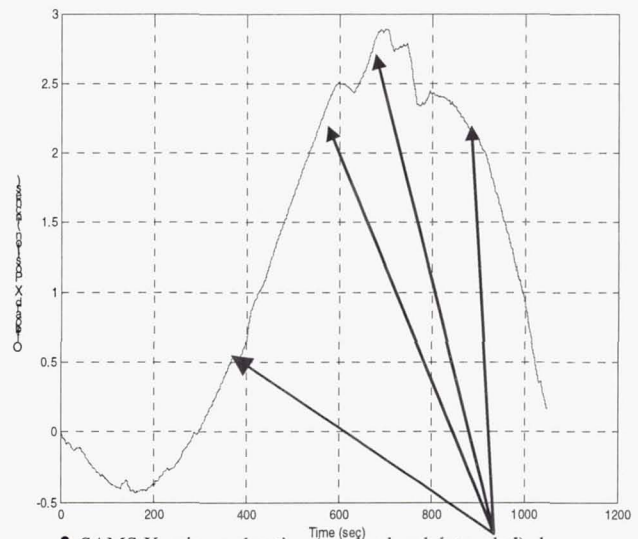
The ARIS system was intended to have a full $\frac{1}{2}$ " sway space in all directions around the rack. Any deviation from this will adversely affect the performance of the system. We have raised this issue to the Microgravity Integrated Products Team (MIPT) who act as ISS uG Systems Integrators. As a result the ISS program is looking at how they can resolve this interference. Another critical ISS problem detected by the ARIS-ICE team data analysis was the documentation of a yet unknown source that

causes anomalous X-axis motion of the Space Station. This motion was previously undetected and is of significant concern as to the affect on the uG environment required for science.

FIGURE 8: IMPACT OF X-AXIS MOTION



**ANTIBUMP MODE IS TRIGGERED BY
FIG. 9: ANOMOLOUS X-AXIS MOTION**



- SAMS X-axis acceleration (resolved and detrended) shows significant station motion
- Station motion causes ARIS relative motion; triggers antibumps

This data was also presented to the MIPT, which is trying to determine the cause of the anomalous ISS X-axis motion. This motion will have to be identified and controlled for a successful and pristine uG environment to be produced.

D. Status of Data Analysis

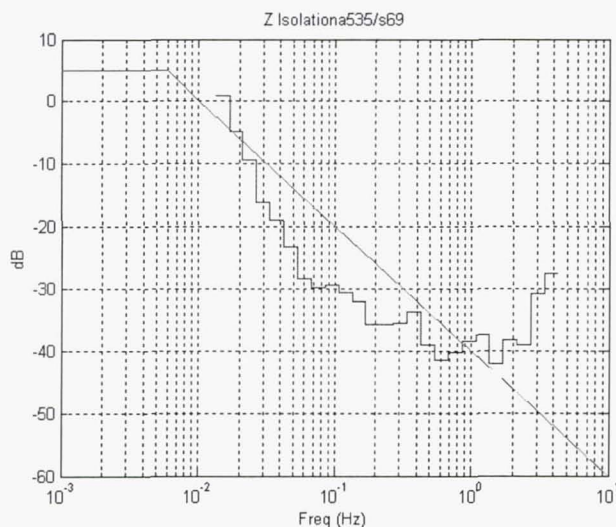
The data analysis on the isolation performance of the ARIS control system conducted in increment 2 was primarily limited to that in the .01 to 1 Hertz frequency range. For the rest of ICE we are looking to cover the full spectrum from .01 through 300 Hertz.

E. Preliminary Research Findings

Our preliminary findings to date show that the performance of the ARIS control system from .01 to 1 Hertz is better than anticipated.

However this does not mean we are home free. The impact of the ISS anomalies is yet to be determined as well as the yet to be tested frequency spectrum regime (to 300 Hz).

FIGURE 10: Z-AXIS ARIS ISOLATION



Typical Z-axis ARIS isolation curve (blue) versus the ARIS Spec (green straight line)

The curve above shows a sample isolation performance curve (valid range is .01-1Hz) of the ARIS system isolating well in the Z-axis.

IV. Conclusion

To date ICE testing has gone exceptionally well especially in increment 2. We have successfully operated all of our hardware. We have successfully received and processed, in real time, the data (as required) to assess performance. Summarized below are some of the ICE team's increment 2 accomplishments.

During increment 2 ICE has validated:

Ground station real time ops/command interfaces
On orbit test setup including all ICE hardware & test computer is 100% functional

During increment 2 ICE validated (cont'd):

Successful data transfer at Seattle and Houston
ARIS snubber performance and containment
New ARIS actuators & pushrod 100% functional
Redesign of ARIS control system is stable
Mass and Inertia testing completed
All ARIS initial checkout testing completed

Over 500 ARIS test runs completed showing:

Sway space violation exists via ARIS range tests
All other ISS interferences identified/removed
Hyper extension testing completed successfully
ISS X-axis motion anomaly exists via testing
All modes of ARIS are fully operational
ARIS performance below 1 Hz is to spec.
Performance of experimental umbilicals is good
Hammer testing is able to provide wideband data
Lap top computer installed & test setup is ready
Dumping/reboost data/impact on ARIS captured
ARIS testing in 7-actuator mode completed
Docked Operations testing started
On orbit replacement and recalibration of ARIS pushrod actuator system successfully completed

Please note, however, that we have just started ICE. We have a highly ambitious schedule and task list with a very long way to go. The ICE experiment will last through increment 4. The on orbit operations have taken somewhat longer than expected mainly due to task complexity and crew availability. The hardware performance, our team's productivity and the crew support have all, however, been excellent. Our current paper work had us returning on UF-2 at the end of increment 4. Everything to date shows that the ARIS performance coupled with the ISS environment will put us very close to meeting the microgravity requirements at that time. The devil is in the details, however, and we need to continue ICE in order to be able to determine where the problems lie. The ICE team had initiated and led a Tiger Team activity in 1998 that identified ISS hardware that may be easily modified or managed. This is the high "bang for the buck" hardware that is most likely to resolve/impact the high probability vibration problem areas. The data from ICE should be able to tell us if problem areas exist and if hardware mod/management is required. For more details on the specifics of this strategy we refer you to our ARIS-ICE website located at: http://iss-www.jsc.nasa.gov/ss/issapt/aris_ice/ This site gives an excellent overview of the approach we are taking as well as containing "weekly" ICE status reports and a detailed "quick look" report on the ICE results to date.

Microgravity Flight Characterization of the International Space Station Active Rack Isolation System

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ABSTRACT

Space flight experiment test results of a Space Station Active Rack Isolation System (ARIS) are presented. The purpose of ARIS is to isolate microgravity sensitive science experiments mounted in Space Station racks from structural vibrations present on the large Space Station orbital structure. The overall objectives of the experiment were 1) to test and evaluate the ARIS design modifications made from 1997 to 2000 as a result of prototype flight testing performed on the Space Shuttle Atlantis, 2) to characterize isolation performance on the International Space Station, 3) to assess the impact that rack payload disturbances have on the microgravity environment, 4) to test alternative umbilicals designed to improve isolation performance, and 5) to gain on-orbit operational experience and validate procedures. The scope of the material presented is limited to microgravity performance issues, so only results related to the first four objectives are presented.

Key performance issues discovered during the first prototype flight test are described first. These issues are related to the behavior of the umbilicals and how to cancel their effects, the dynamic response of the rack and control stability, identification of sources of all dominant vibrations above 1.0 Hz, the impacts of rack rotation on the microgravity performance at all locations in the rack, and the performance impact due to the

constraint on the range of relative displacement between the Station and the rack. The controller design is then presented and the performance issues are addressed. A description of the ARIS International Space Station Characterization Experiment (ARIS-ICE) test hardware and configuration is described. Several sets of alternate umbilicals and station shaker hardware were developed and used during the experiment. ARIS actuators were also used to determine the stiffness of the umbilicals and to obtain a response of the rack and the station interface. Tests were also conducted with the payload fans on and off to determine their impact on performance. Isolation tests during crew awake and sleep periods, and during station shake tests were obtained. These characterization and isolation test results are presented.

INTRODUCTION

One of the primary objectives of the International Space Station (ISS) is to provide an acceleration environment suitable for microgravity class science experiments. Microgravity experiments include many crystal growth and fluid experiments that are very sensitive to very low quasi-steady frequency acceleration. The maximum acceleration level considered acceptable for most microgravity experiments is specified in the International Space Station requirement [1] and is shown in Figure 1. This requirement constrains the root-mean-square (rms) acceleration level for one-third octave bandwidths. As can be seen in the figure, the

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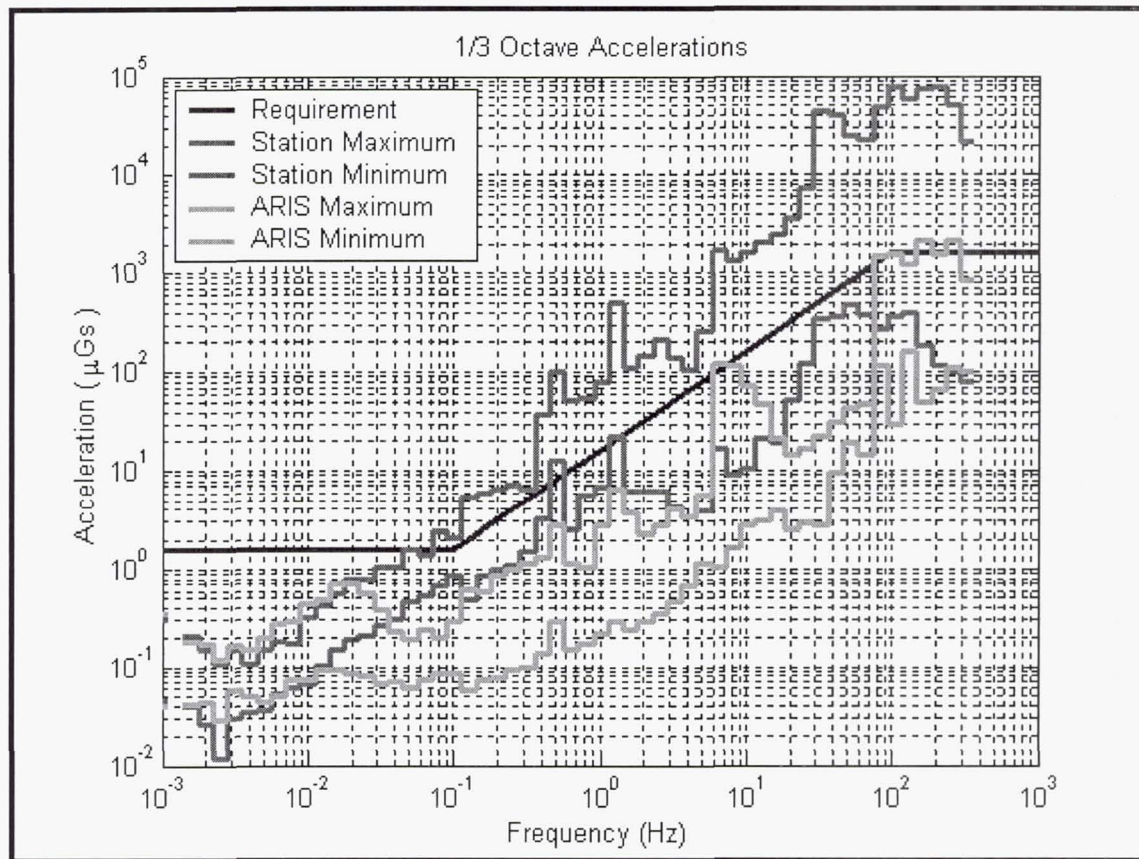


Figure 1 : Science Requirement and Measured Acceleration Levels
Station Vibration Above 5 Hz Excited With Hammer

rms acceleration magnitudes below 0.1 Hz must be less than 1.6 micro-G, and above 100 Hz less than 1.6 milli-G. Early predictions indicated that the station acceleration environment could be as much as 10 times higher than the requirement.

To insure that the requirement was met at certain payload rack locations in the Space Station, an Active Rack Isolation System (ARIS) was built and tested on-orbit. The first prototype flew on a shuttle mission to the Russian MIR Space Station (STS-79) in September of 1996, and the first flight unit recently flew in April 2001 and was installed on the International Space Station in the U.S. Lab (STS-100). There are currently three types of microgravity science racks that plan to use ARIS to isolate their payloads. They are the EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) rack, the Fluid Combustion Facility (FCF) rack, and the Materials Science Research Facility (MSRF) racks. All of these racks use the International Standard Payload Rack shell, mounting posts, and utility interface panel. Unique payload hardware is added to build each facility. An EXPRESS rack is shown in Figure 2, and is the first ARIS rack that was tested on

the Space Station. The rack is outfitted with power, communications, and cooling systems to support microgravity payloads. Payloads can be mounted at any of eight standard Shuttle mid-deck lockers or in two Standard Interface Rack (SIR) drawers at the bottom of the rack.

THE ARIS CONCEPT

The ARIS concept is to isolate the entire rack. The rack is isolated by detaching it from the station structure (so that it is free to move) and then holding it motionless via an active control system. The active control system consists of inertial accelerometers mounted in the rack and voice coil type actuators placed between the rack and the station. Umbilicals remain connected to the rack to support power, fluid cooling, and data communication as required by the science payload. Undesirable forces transmitted from the station to the rack by the umbilicals are canceled by the active control system.

The ARIS hardware configuration is shown in Figure 3. Acceleration is sensed at accelerometer heads located in

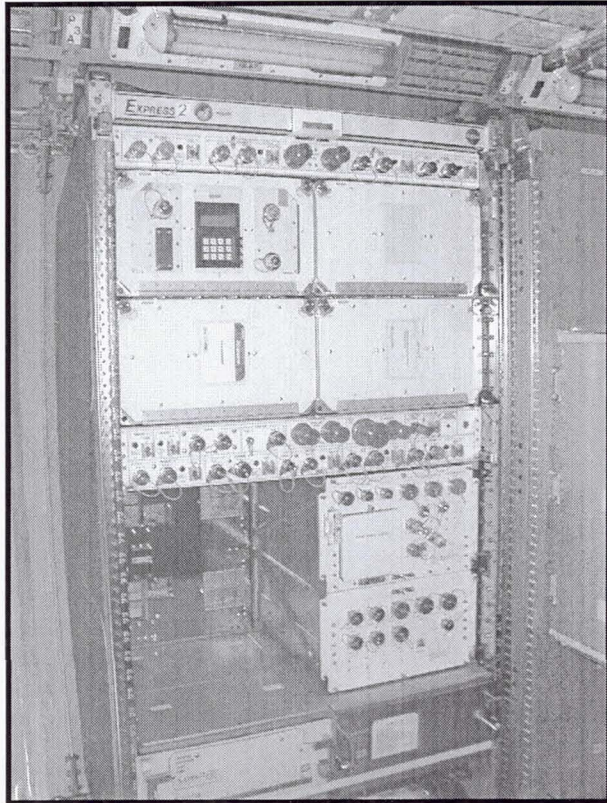


Figure 2 : Space Station EXPRESS Rack

the corners of the rack. Each head contains an orthogonal set of single axis proof-mass accelerometers. Hard stop bumpers located on the front and bottom of the rack prevent the rack from impacting non-ARIS structure. The bumpers constrain the rack so that it can not move more than 0.5 inches in any direction from its center position. Low authority position feedback is blended with acceleration feedback to keep the rack away from the bumpers so that Station structural vibrations may be isolated without impact interruptions. Further design details can be found in Reference [2].

Control algorithms are executed by a digital controller located in the bottom of the rack. Control features include kinematic and dynamic decoupling used to account for the mass properties of the payload, the stiffness properties of the umbilicals, and the skewed locations of the actuators and sensors. Decoupling is also used to formulate an intuitive single-input-single-output (SISO) approach by resolving and compensating the translational and rotational motion of the rack. This approach simplified control parameter selection, and system testing, and facilitated the

implementation of non-linear "anti-bump" algorithms used to limit the range of rack motion.

The Prototype Experiment

The ARIS prototype system was flown on the Space Shuttle Atlantis to prove the system concept before flight production units were built. ARIS flew in the Spacehab double module located in the shuttle bay and was mounted in an adapter frame with Space Station-like interfaces. The primary objective of the mission was realized by successful completion of both nominal and contingency operations, and collection of performance data taken over an 8 day planned test period [3]. It was successfully demonstrated that, 1) the entire space station rack with large standard space station rack utilities could isolate the payload from sub-tenth Hz vehicle motion, 2) the skewed non-collocated multi-input-multi-output (MIMO) system could be stabilized using an intuitive based control architecture using SISO feedback systems combined with mass and stiffness system identification and decoupling techniques, 3) the relative motion between the vehicle and the rack was less than 0.5 inches in any direction when the vehicle was in a free-drift microgravity operational mode, 4) the non-linear impact prevention algorithm successfully prevented hard impact during vernier thruster firing events, and 5) the rack motion response to accelerometer noise drift did not result in excessive rack motion.

Four key performance issues identified were 1) the isolation performance below 1 Hz was less than predicted, 2) the isolation performance was better at the center of gravity of the rack than at the far corners of the rack, 3) there were oscillations around 100 Hz on the

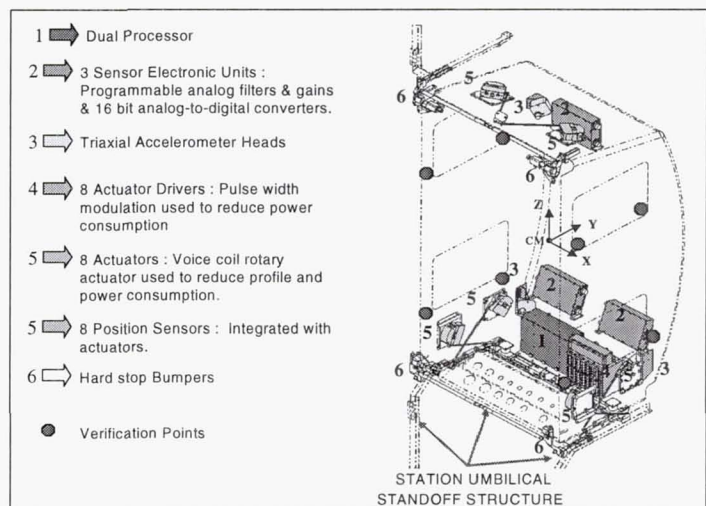


Figure 3 : ARIS Payload Rack

rack that may have been driven by the controller, and 4) that the isolation performance above 1 Hz could not be fully resolved because the vehicle acceleration levels were attenuated to levels below the quiescent background noise floor. Post mission analysis and ground testing showed that the first two issues were related to the non-linear stiffness behavior of the umbilicals, that the third issue was due to bad actuator drivers, and that the isolation performance above 1 Hz could be resolved if the vehicle acceleration was higher. Solutions were developed to address each of these issues and improve performance.

THE ARIS INTERNATIONAL SPACE STATION CHARACTERIZATION EXPERIMENT (ARIS-ICE)

The eight days of ARIS prototype testing had great value, and results showed that further testing in a microgravity environment was needed to resolve performance and operational issues, and test design modifications made as a result of the prototype testing. An ISS Payloads Office led partnership of Boeing, Glenn Research Center (GRC), Johnson Space Center (JSC), and Marshall Space Flight Center (MSFC) concluded that the first months of on-orbit operation of the first ARIS Space Station flight unit should be reserved for characterization testing.

Full characterization testing required additional hardware. This hardware included a shaker system to excite station vibration, space station acceleration measurement systems to measure the vibration, and a computer to support command and data handling. The test configuration is illustrated in Figure 4. Space station accelerations were measured using the Space Acceleration Measurement System (SAMS) and the Microgravity Acceleration Measurement System (MAMS). The SAMS Sensor Enclosures (SEs), or sensor heads, each contain an orthogonal set of single axis accelerometers and were used to measure Station acceleration above 0.01 Hz. Three heads were mounted around the rack, one at the top actuator interface, one at the bottom umbilical interface, and one on the adjacent rack umbilical interface panel. The MAMS unit was used to measure very low frequency accelerations below 0.01 Hz. The rack accelerations were measured using the ARIS acceleration measurement system and one SAMS head located on the Physics of Colloids in Space (EXPPCS) experiment locker. To help resolve isolation above 1 Hz, a shaker was mounted on station structure beneath the rack and used to excite station vibration. The crew also used a small hammer to excite the structure by tapping at specified locations around the rack. Ground command, data handling, and data storage capability was provided by the ARIS-ICE Payload On-orbit Processor (POP). Flight data was collected by the

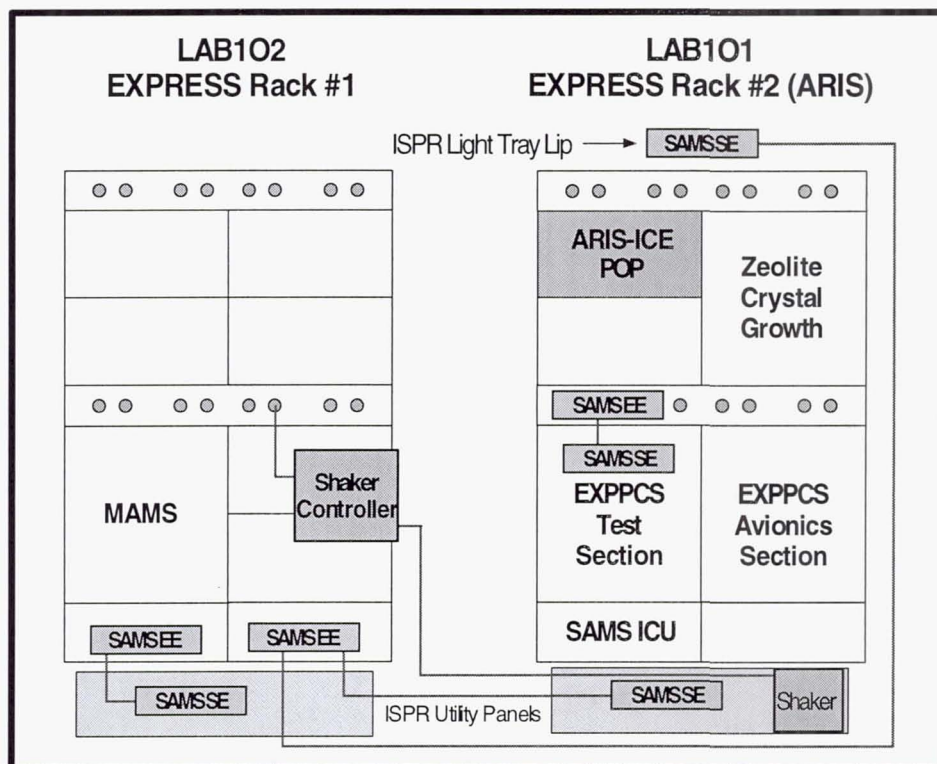


Figure 4 : SPACE STATION FLIGHT EXPERIMENT CONFIGURATION

POP for one full year beginning in June of 2001 and over 1700 test runs were completed.

The rack was launched with the POP in the upper left locker and with EXPPCS using all 4 lower middeck lockers. The SAMS Interim Control Unit (ICU) was located in the bottom left SIR drawer, and spare ARIS-ICE umbilicals were located in the right SIR drawer. The locker below the POP was used for stowage of other ARIS-ICE hardware, such as the shaker, when not in use. The remaining top 2 middeck locker locations remained empty until the Zeolite Crystal Growth (ZCG) payload was added in December of 2001.

Umbilical Alternatives

Power, thermal cooling, vacuum, and data lines are provided to all station racks at interfaces below the rack. A list of the umbilicals provided is listed in Table 1 for the station ARIS racks, and for the prototype rack.

The prototype set of umbilicals had been designed to have low stiffness to improve isolation performance, but the performance benefits were not fully realized due to hysteresis. Post prototype mission ground data showed that the stiffness increases as the amplitude of motion decreases. The amplitudes of motion are small at higher frequencies, resulting in higher stiffness and lost performance. The stiffness also varies as the rack moves away from its center position. Prior to the mission, the stiffness was only measured over one large amplitude of motion. The lower large motion stiffness values, not the small motion higher stiffness values, were used in the controller to cancel stiffness.

The ARIS controller was designed to allow for measurement of the linear stiffness forces and cancel them, but has no provisions for canceling the hysteretic and flexible dynamic forces. The dynamic forces had never been measured prior to the prototype experiment. Following the experiment, an inexpensive ground test bed was made utilizing experiment hardware to measure the stiffness of each individual umbilical and its dynamic response in two directions [4]. NASTRAN models were also built and correlated to the test data. From this it was found that the large twisted copper power umbilicals accounted for 50 percent of the stiffness and had a significant mode at 10 Hz. It was also obvious that the stranded wire had significant hysteresis. Several design options were tested and alternative sets built and flown as part of the ARIS-ICE mission. These options are listed in Table 2.

The prototype design used a heavier gauge wire to allow for 6 kW power. It had standard pressure extruded insulation, and like most of the umbilicals, was looped

Function	PROTO	EXPRESS	FCF	MSRF
Ground Strap	X	X	X	X
Main Power	X	X	X	X
Safing Power	X	X	X	X
1553 A		X	X	X
1553 B	X	X	X	X
Video		X	X	X
High Rate Data	X	X	X	X
FDS		X	X	X
Ethernet	X	X	X	X
Ethernet Data	X			
Cooling Water	X	X	X	X
Cooling Water	X	X	X	X
Waste Gas		X	X	X
Vacuum Resource			X	X
GN2	X	X	X	X
Laptop	X ¹	X	X	X
Pump Power	X ²			
Fiber Optic			X ³	
1. Used Video Interface 2. Used FDS Interface 3. Data cable run between two adjacent FCF racks FCF – Fluid Combustion Facility MSRF – Materials Science Research Facility				

Table 1 : Umbilical Configurations

to reduce its stiffness. The lighter gauge wire (3 kW) was built with loose sleeve insulation to reduced stiffness, and the loop was removed to eliminate the 10 Hz mode. The cooling water and gas hoses were also improved by using a softer type of material.

ARIS-ICE Controller Design

A new controller was designed to improve performance based upon the experience gained from the prototype experiment. The significant changes are listed below.

1. Filters were added to gain-stabilize the EXPRESS structural modes, and the bandwidth of the controller was increased as much as possible. A test correlated NASTRAN model of the EXPRESS rack was developed by Boeing and was added to the Matlab control model.

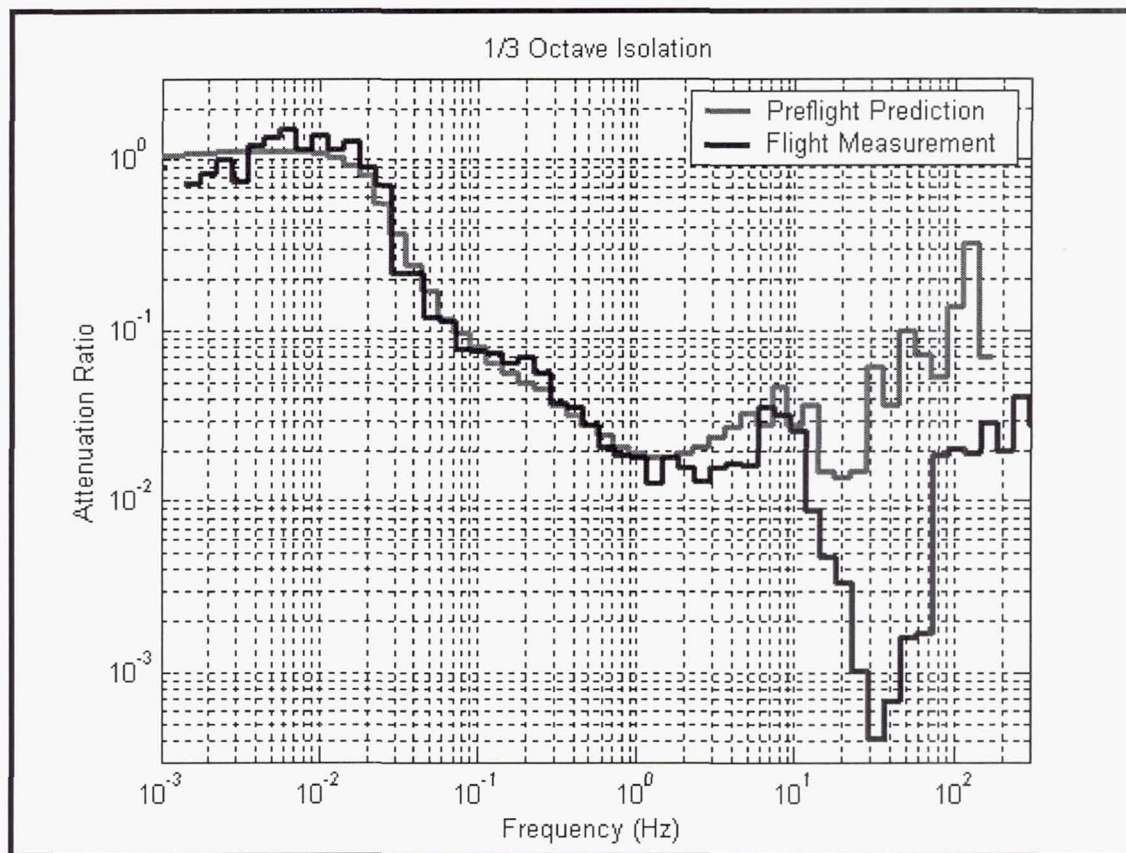


Figure 5 : Predicted and Measured Isolation Performance

2. The low frequency acceleration feedback gain was minimized to reduce the response to acceleration drift noise. The acceleration drift was bounded using quiescent test data collected during the prototype flight test.
3. The position authority on the rotation axes was increased to reduce rack rotations. This was done to improve the performance at locations away from the rack center of gravity. Rack rotations caused by Station translation (umbilicals torque rack) will decrease. But the rack will follow station rotation, so performance will only improve if station rotations are small.
4. The stiffness cancellation parameters were changed to use the larger small amplitude stiffness instead of the smaller large amplitude stiffness. More linear stiffness is cancelled because the small amplitude stiffness is greater than the large amplitude stiffness. This improves performance over the entire bandwidth of the controller.
5. The shape of the isolation response was changed so that ARIS isolated less around 0.01 Hz. This was done to prevent the rack from bumping into its hard stops due to low-frequency station motion. Station acceleration predictions showed that isolation around 0.01 Hz was not needed, and the total

motion between the vehicle and the rack could be reduced significantly by a small change to the shape of the isolation response. Performance at 0.05 Hz and above was maintained.

The preflight isolation performance prediction using the new updated controller is shown in Figure 5. The prediction is the worst expected performance at all payload attach locations in the rack. The model used to make the prediction was ground test correlated and included models of the rack and umbilical dynamics, uncertainty in the mass properties of the rack, and variations in the stiffness of the umbilical. Umbilical dynamics impacted performance above 7 Hz and the rack dynamics significantly impacted performance above 30 Hz. Mass and stiffness uncertainty impacted performance above 1 Hz the most. The performance prediction does include 12 db of performance improvement at 10 Hz resulting from using the 3 kW unlooped power umbilicals.

ARIS-ICE TEST DATA

The alternate power umbilical designs were each installed and stiffness and isolation performance data collected. Umbilical stiffness results are presented first,

followed by isolation results. The isolation performance with the umbilical set that will be installed on all future station ARIS EXPRESS racks (ARIS-ICE C) is presented. This data was taken from crew awake and station tap periods. Motion between the station and the rack during a typical isolation period is also presented. Next, data is compared with the EXPRESS AAA fan and the ARIS-ICE payload fans on and off to determine their impact on performance. The flexible response of the EXPRESS rack is shown and stability margins discussed. Finally, performance is predicted when the station structure assembly is complete and all station vibration sources operating.

Umbilical Stiffness Results

The measured stiffness ranges of four flight umbilical configurations are listed in Table 2. The range was determined by measuring the stiffness for small amplitude motion (0.05 inches peak to peak) and for large amplitude motion (0.5 inches peak to peak). The stiffness is higher for small amplitudes. As can be seen in the table, the two 3 kW teflon jacketed power umbilicals (ARIS-ICE C) alone reduced the small amplitude stiffness of the entire baseline 6 kW set (ARIS-ICE B) by 2.5 to 4.5 times. The range of stiffness is also significantly reduced. Addition of the gaseous nitrogen (GN2), which is the only non-looped hose, doubled the small amplitude stiffness. It was originally designed to be looped, but the hose had to be redesigned to meet pressure requirements. The hose was changed from a soft viton material which could be

performed in a loop shape to a bellows type hose with a braided sleeve.

Isolation Performance

Station and rack acceleration levels during crew awake periods are shown in Figure 1. Several windows of data were used and the maximum and minimum levels are shown. The acceleration magnitudes are plotted as the root-mean-square (rms) acceleration level per one-third octave bandwidths. The Station level was resolved from the SAMS head located on the umbilical standoff structure beneath the rack. The rack level was resolved from the three ARIS heads on the rack. Each head has three linear accelerometers that are orthogonal to one another. The rms 1/3 octave band level was computed for each accelerometer, then the three levels for each head were root-sum-squared to produce a single magnitude. The rack head accelerations were compared over all windows and the maximum and minimum envelopes are plotted. The envelope of the SAMS head accelerations is also plotted.

A 5-hour test and 9-minute test were used to compute the acceleration and isolation levels shown. The data was split into windows as listed in Table 3.

Flight Engineer Carl Walz excited the Station Structure by tapping the umbilical standoff structure using the small hammer during the 9-minute test with the AAA fan turned off. Typical Station acceleration levels flatten off above 5 Hz to levels shown at about the

Power Set	ARIS-ICE B	ARIS-ICE A	ARIS-ICE C	ARIS-ICE C
Main Power	6 kW Looped Pressure Extruded Silicon Jacket	6 kW Unlooped Loose Expanded Teflon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket
Safing Power	6 kW Looped Pressure Extruded Silicon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket	3 kW Unlooped Loose Expanded Teflon Jacket
GN2 Included	No	No	No	Unlooped Teflon Bellows Braided Nomex Sleeve
X Stiffness (lb/ft)	84 - 210	47 - 73	47 - 64	65 - 125
Y Stiffness (lb/ft)	99 - 227	66 - 136	65 - 93	97 - 193
Z Stiffness (lb/ft)	109 - 386	58 - 123	58 - 85	85 - 164

Table 2 - Power Umbilical Configurations and Stiffness

Test	Number Of Windows	Window Duration (sec)	Overlap	Frequency Plotted
5 Hour	14	2097.152	50 %	0.001 – 0.1 Hz
5 Hour	121	262.144	50 %	0.1 Hz – 5 Hz
9 Minute	127	8.192	50 %	5 Hz – 300 Hz

Table 3 : Performance Data Analysis Parameters

Station Minimum above 20 Hz. The minimum levels were obtained during windows in-between the hammer strikes. As can be seen, these levels are too low to allow accurate measurement of isolation performance. The maximum levels obtained during the hammer strikes are up to two orders of magnitude higher, thus providing a better estimate.

The corresponding isolation is plotted in Figure 5. The isolation was computed for all three ARIS heads, but only the worst of the three is shown. As can be seen in the figure, the isolation measurement follows the prediction up to 10 Hz, then becomes much better. The isolation performance was expected to be generally better than the prediction, but the prediction was made with the softer GN2 hose. Better performance was realized when the GN2 hose was removed.

Station Motion

Relative motion between the station and the rack is shown during a 1-hour test run in Figure 6. The amount of motion is important because the total range of relative motion is limited to 1 inch in each direction. As can be seen there is significant motion in the X direction. It was determined that the X axis motion was due to the station moving in response to crew movement down the module centerline. This was validated by station acceleration measurements and by correlated motion observed during video transmission. Conservation of momentum requires that the velocity of the center of gravity of the entire station and its enclosed contents remain constant. This means that the station will move in proportion to crew motion as follows,

$$X_{\text{Station}} = \frac{\text{Crew Mass}}{\text{Station Mass}} X_{\text{Crew}}$$

The total distance that a crew member may move down the centerline (X direction) of all the modules is listed in Table 4. The Station configuration is shown in Figure 7. The total station weight at the time of the test was 283755 lbs. So, the station will move 0.96 inches if one crew member weighing 175 lbs moves the length of the station. The station weight will increase at

assembly complete to around 1 million lbs, so the motion will decrease accordingly. The ARIS controller uses a non-linear algorithm to generate anti-bump commands to insure that the relative range of motion is not violated. These anti-bump commands are invoked regularly due to crew motion but are limited to 15 micro-Gs or less. The measured accelerations shown in Figure 1 include the effects of the anti-bump commands, which tend to slightly increase the rack acceleration below 0.1 Hz.

Module	Length (feet)
Service	43
Zarya	41.2
Unity	18
Destiny	28
Total	130.2

Table 4 : Length Of Station Modules

Impacts of the AAA fan

Data was collected with the Avionics Air Assembly (AAA) and the POP Fans On and Off. Data was also collected with the POP fans On and the AAA fan Off. The AAA fan is provided by EXPRESS to cool the payloads in the rack. It draws payload exhaust heat to the rear of the rack and passes it across an air-to-water

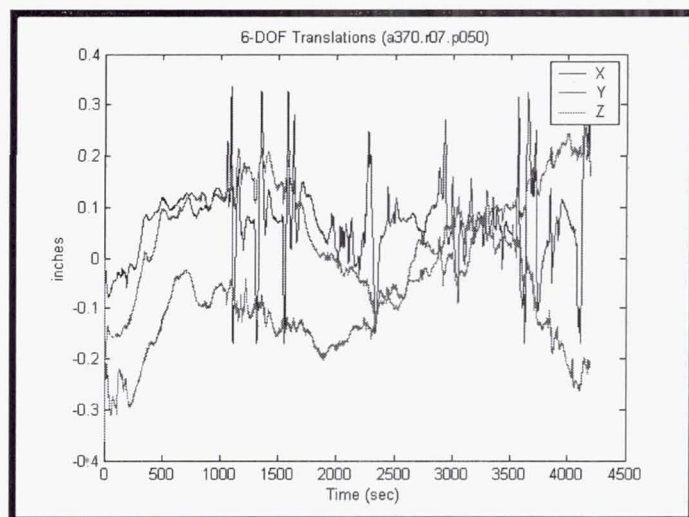


Figure 6 : Relative Motion Between Station and Rack During Active Isolation

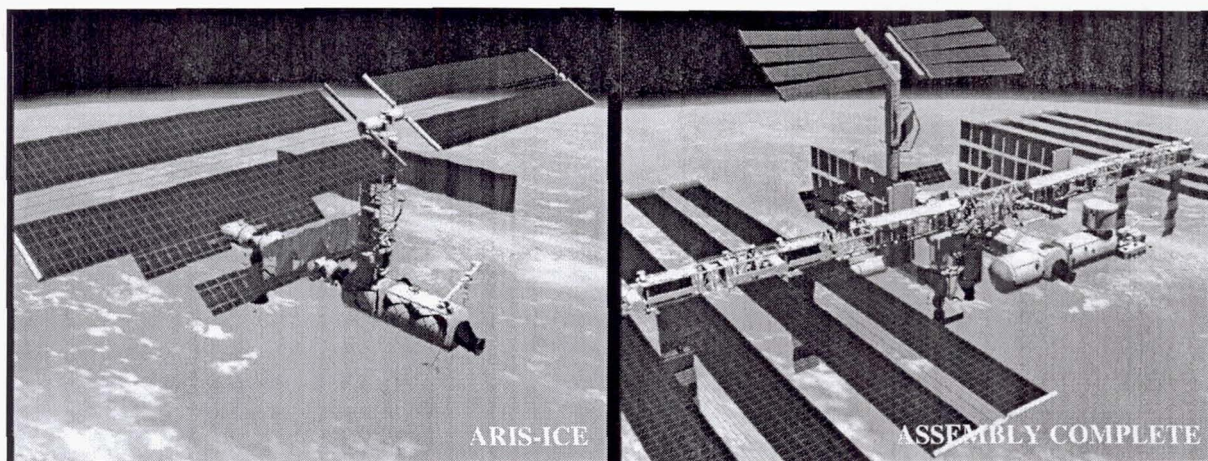


Figure 7 : Station Configurations

heat exchanger. It is mounted in the back of the rack behind the locker mounting panel. The POP has two standard fans in the locker to circulate air. The head acceleration levels with the fans on and off are shown in Figures 8 and 9.

Figure 8 data was collected for 150 seconds and subdivided into 35 windows (50% overlap) of 8.192 seconds each. The maximum levels over all windows and over all the heads are shown. The ARIS isolation system was inactive or passive during the data collection with all fans on (AAA On), and actively isolating during the fan off tests (AAA Off and AAA & POP Off). The stiffer 6 kW power umbilicals (ARIS-ICE B) with the 10 Hz mode were installed for these tests.

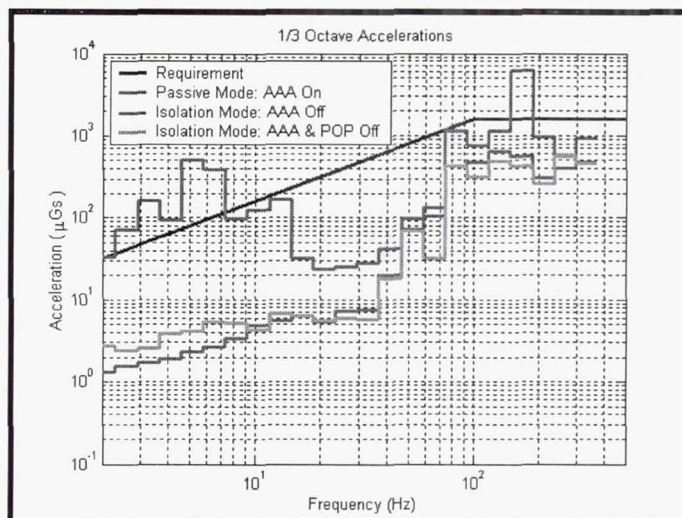


Figure 8 : Maximum Head Accelerations
With Fans On and Off

The accelerations are expected to be higher below 30 Hz during the passive test because the rack is free to oscillate on the umbilicals. Above 30 Hz there is no difference between the passive and active isolation state. This is because the controller feedback rolls off at 30 Hz, so the rack behaves passively above 30 Hz even when in an active isolation state. As can be seen the POP fans have very little effect, but the AAA drives significant vibration in the 80 to 200 Hz region resulting in levels higher than the requirement at 180 Hz. The PSD's of the acceleration show many modes between 80 and 200 Hz, with the highest energy at 90 and 184 Hz.

Figure 9 data was collected with the AAA and POP fans on. The test duration was 524 seconds and again subdivided into 8.192-second windows. The levels at the three ARIS heads and the SAMS head mounted on EXPPCS are shown. The levels are the maximum over all windows.

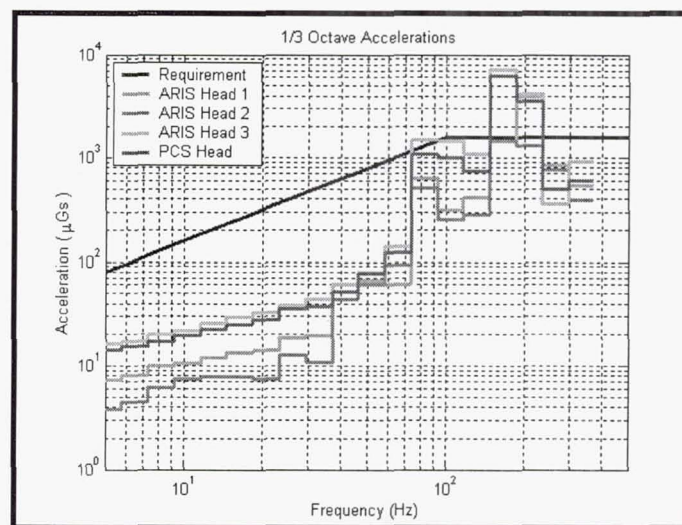


Figure 9 : Head Accelerations
With Fans On and ZCG Installed

As can be seen, the levels vary at higher frequencies. One ARIS head meets the science requirement over all octave bands.

Flexible Response Of The Rack

The flexible response of the rack was measured by commanding the ARIS actuators to drive the rack in a single control direction. The commanded force was a combination of superimposed sinusoids spaced every 1/30 of an octave in frequency between 30 and 300 Hz. The response in each control direction is shown in Figure 10. The first fundamental mode was measured to be 47 Hz. Strong modes also appear at 112, 146 thru 184, and 285 Hz. The objective of this test was to determine what the control stability margins were. The controller filtering characteristics had been designed prior to flight based on a ground test correlated NASTRAN model.

The preflight open loop acceleration response prediction of the controller and flexible rack is shown in Figure 11. The flexible rack model did not include modes past 150 Hz. A 30 Hz 2nd Order Filter, a 30 Hz 40 db stop band elliptical filter, and a 119 Hz notch filter were required to stabilize the modes above 35 Hz. The first fundamental mode was predicted to be 42 Hz. Preflight ground test data showed that the first mode had around 2 percent damping. The high damping was attributed to the fact that the mode shape required the entire rack to deflect and twist. For the most part, other higher modes were merely local interactions between concentrated masses and panels with damping between 0.5 and 1 percent. This is consistent with the flight data which shows that 30 db attenuation is required at 47 Hz, and at least 50 db is required above 100 Hz. So, heavy filtering was still required.

ASSEMBLY COMPLETE PREDICTION

The station structure at assembly complete will be larger (see Figure 7) and have more vibration sources as payloads are added. The Station acceleration prediction at assembly complete is shown in Figure 12 [5]. The isolation performance shown in Figure 5 was used to predict the EXPRESS rack acceleration levels shown in Figure 11 at assembly complete. The prediction meets the science requirement. Work is currently being conducted to predict the performance for the Fluids Combustion Facility and the Microgravity Science Research Facility. Two major differences are that these

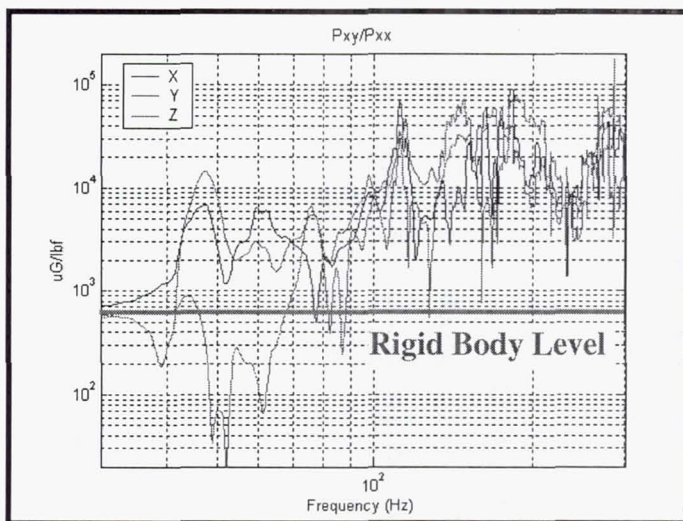


Figure 10 : Measured Forced Response Of The Rack

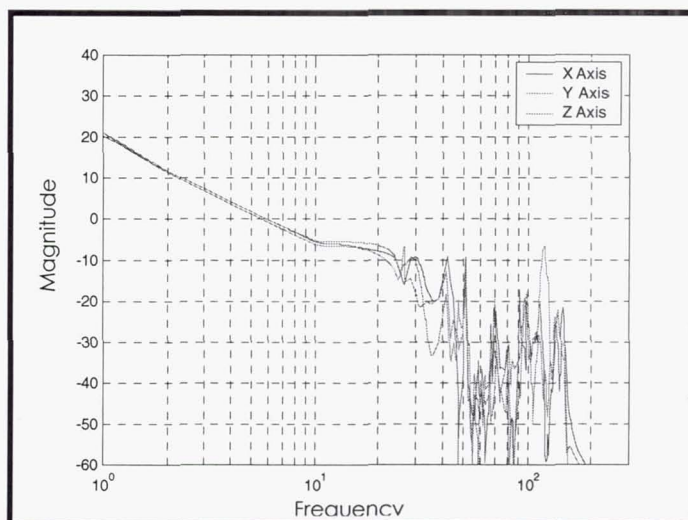


Figure 11 : Preflight Predicted Open Loop Response Stability Margins

facilities use a large Vacuum Resource umbilical and that the payload structure is significantly different.

CONCLUDING REMARKS

Valuable data has been collected during the ARIS International Space Station Characterization Experiment. ARIS has consistently performed extremely well over the past year such that station vibrations were isolated to levels well below the science requirement. This success was a result of lessons learned from the prototype experiment and design changes made to the umbilicals and control parameters. The unlooped GN2 hose increased the overall umbilical set stiffness, but performance was maintained mainly

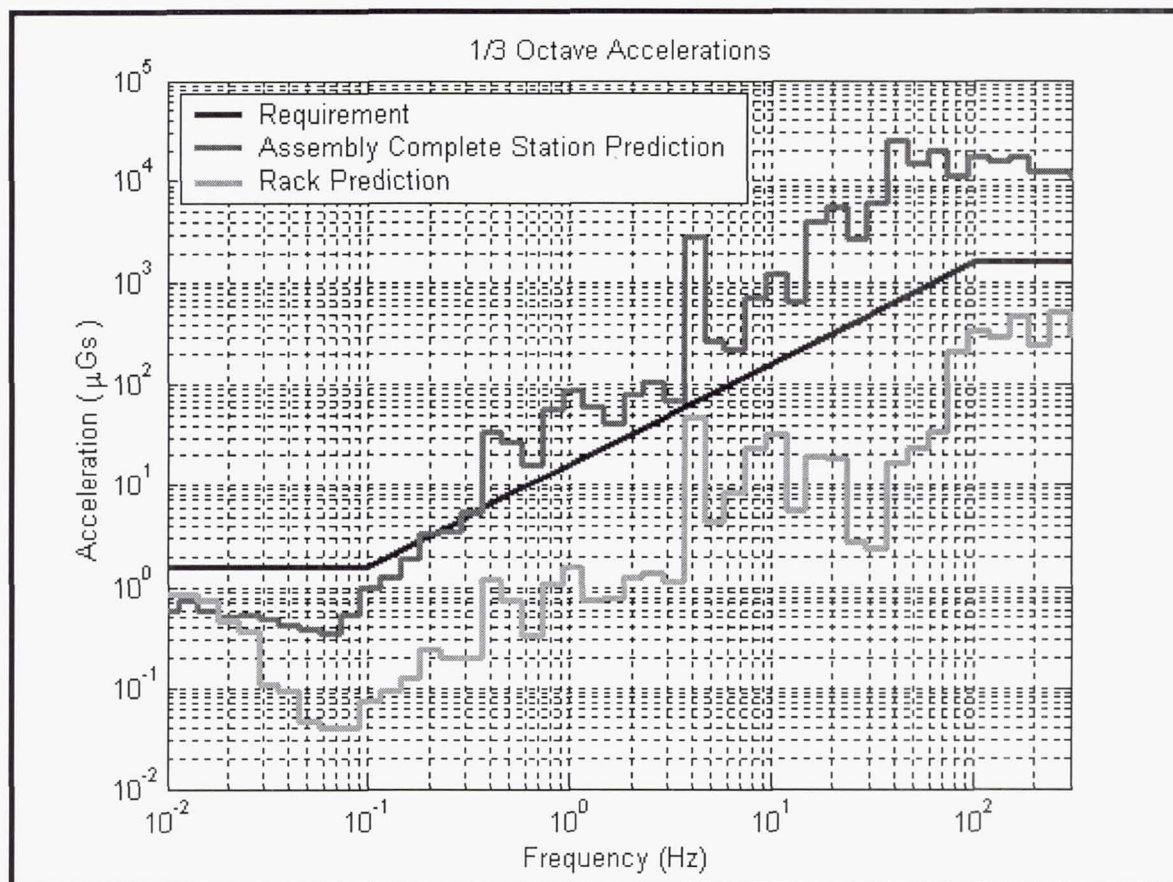


Figure 12 : Predicted Station and EXPRESS Acceleration Levels At Assembly Complete

due to the significant decrease in overall stiffness provided by improved power umbilicals developed and tested as part of ARIS-ICE. The expected acceleration levels on an ARIS isolated EXPRESS rack after station assembly is complete is expected to meet the microgravity science requirement at frequencies below 100 Hz. Science payloads need to be designed so that vibration is not transmitted to their own science location by their own vibration sources if the science requirement is to be met at all frequencies. Performance for other ARIS isolated facilities will be dependent on the facility rack structure and on the stiffness and dynamics of the Vacuum Resource umbilical. Work on characterizing the Vacuum Resource umbilical is currently in progress. A detailed, final report of the ARIS-ICE mission and test results will be provided to address the volumes of data collected.

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